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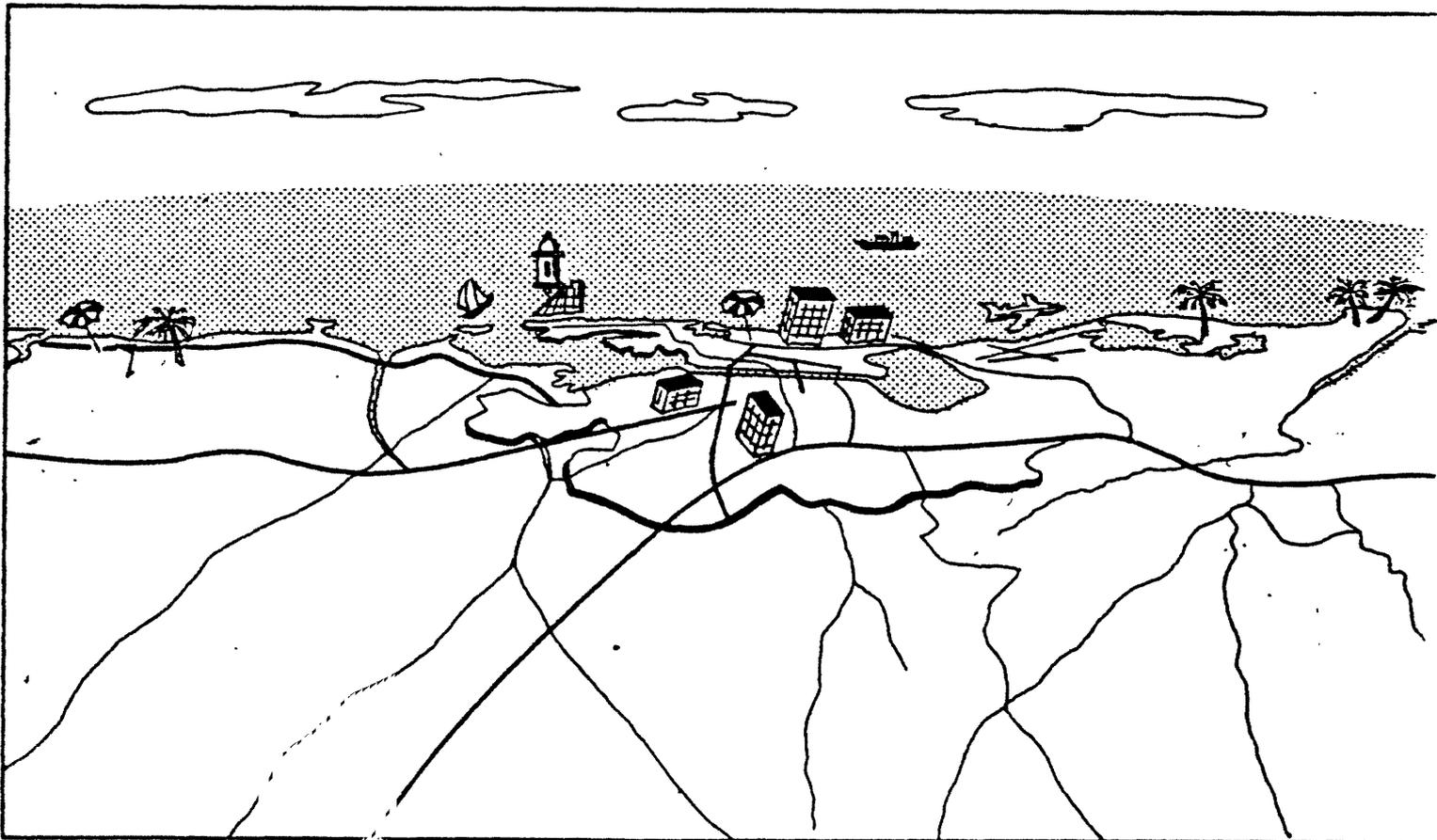
**GROUND WATER IN THE SAN JUAN
METROPOLITAN AREA,
PUERTO RICO**

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 41-75



**Prepared in cooperation with
Commonwealth of Puerto Rico**



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PUERTO RICO

By Henry R. Anderson

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July 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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Factors for converting English units to International System (SI) units

Multiply English units	By	To obtain SI units
<u>Length</u>		
inches (in)	25.4	millimetres (mm)
inches (in) . . . . .	.0254	metres (m)
feet (ft) . . . . .	.3048	metres (m)
miles (mi)	1.609	kilometres (km)
<u>Area</u>		
square miles (mi ²)	2.590	square kilometres (km ²)
<u>Volume</u>		
cubic feet (ft ³)	28.32	litres (l)
cubic feet (ft ³) . . . . .	.02832	cubic metres (m ³)
cubic feet per second-day [(ft ³ /s)-d] .	2447	cubic metres (m ³)
gallons (gal)	3.785	litres (l)
gallons (gal)	3.785 x 10 ⁻³	cubic metres (m ³)
million gallons (10 ⁶ gal)	3785	cubic metres (m ³)
million gallons (10 ⁶ gal)	3.785 x 10 ⁻³	cubic hectometres (hm ³)
<u>Flow</u>		
cubic feet per second (ft ³ /s)	28.32	litres per second (l/s)
cubic feet per second (ft ³ /s) . . . . .	.02832	cubic metres per second (m ³ /s)
gallons per minute (gal/min) . . . . .	.06309	litres per second (l/s)
gallons per minute (gal/min)	6.309 x 10 ⁻⁵	cubic metres per second (m ³ /s)
million gallons per day (10 ⁶ gal/day) .	43.81	litres per second (l/s)
million gallons per day (10 ⁶ gal/day) .	.04381	cubic metres per second (m ³ /s)
<u>Other</u>		
hydraulic conductivities (ft/day) . . . .	.3048	metres per day (m/day)
million gallons per day per square mile [(10 ⁶ gal/day)/mi ²]	16.92	litres per second per square kilometres [(l/s)/km ²]
specific capacities [(gal/min)/ft] . . . .	.207	litres per second per metre [(l/s)/m]
specific capacities [(gal/min)/ft] . . . .	.207 x 10 ⁻³	cubic metres per second per metre [(m ³ /s)/m]
transmissivities (ft ² /day) . . . . .	.0929	metres squared per day (m ² /day)

NOTE: To convert degrees Celsius (°C) to degrees Fahrenheit (°F) use the following equation:

$$^{\circ}\text{F} = 9/5 (^{\circ}\text{C}) + 32.$$

GROUND WATER IN THE SAN JUAN
METROPOLITAN AREA, PUERTO RICO

by Henry R. Anderson

ABSTRACT

San Juan is on the north coast of Puerto Rico, a coastal lowland of seaward dipping Tertiary formations which lap up on Cretaceous volcanic mountain core.

Ground water in San Juan has played a declining role in water supply since the completion of the Lofza reservoir project in the early 1950's. Ground-water yield is limited because the aquifers are small and susceptible to seawater intrusion.

Wells tapping the more permeable weathered zone in the volcanics may obtain as much as 300 gal/min (19 l/s) but specific capacities of wells are low, 1.4 (gal/min)/ft of draw-down [0.29 (l/s)/m]. The volcanic rocks contain the least mineralized ground water in San Juan, averaging about 250 mg/l dissolved solids.

The basal Tertiary formation, the San Sebastián Formation, together with the lower part of the Cibao Formation, is a confined aquifer made up mostly of sand and marly limestone less than 330 ft (100 m) thick. Average yields are 240 gal/min (15 l/s), with specific capacities of wells of 3.1 (gal/min)/ft of drawdown [0.64 (l/s)/m] and transmissivities of 1,000 ft²/day (93 m²/day). Recharge is estimated to be 0.7 (10⁶ gal/day)/mi² [12 (l/s)/km²].

The Cibao Formation in general, and clay beds in particular, make up the semi-impermeable zone between the confined sand and the limestone that forms the unconfined aquifer.

Yields in Aguada Limestone of the unconfined aquifer are as much as 2,500 gal/min

(160 l/s) and average 540 gal/min (34 l/s). Average specific capacity of wells is 41 (gal/min)/ft [8.5 (l/s)/m]. The freshwater lens along the coast is less than a mile wide in San Juan. Consequently seawater intrusion is a threat. The Aymamón Limestone, which overlies the Aguada Limestone, is highly permeable but for the most part contains salt water. In Sabana Seca, a freshwater-bearing zone has transmissivity of 200,000 ft²/day (1.86×10^4 m²/day).

Ground-water recharge to the limestone unconfined aquifer is on the order of 1 (10^6 gal/day)/mi² [17 (l/s)/km²]. Coastal discharge to the sea is about 4.5 (10^6 gal/day)/linear mi [0.20 (m³/s)/linear km] of coast.

Ground water becomes less mineralized inland from the ocean. Median concentrations of dissolved solids, hardness, and bicarbonate are 525, 295, and 300 mg/l for the Aguada and Aymamón Limestones, which are nearest the sea; and 363, 195, and 226 mg/l for the San Sebastián and Cibao Formations, which lie farther inland.

A summary of the water budget for the Río de Bayamón shows that for a typical average rainfall of 64 in (1,625 mm) about 28 in (710 mm) is runoff, and 36 in (915 mm) evapotranspiration, assuming storage in a basin is constant. Ground-water flow from weathered volcanic rocks to streams and the sedimentary rock aquifers is about 15 in (380 mm) annually, about half the total runoff.

Ground water continues to play a small role for water supply in the San Juan area. The limited quantity available, perhaps 30×10^6 gal/day (1.3 m³/s), is currently about half used. Nevertheless, ground water is important for use in special situations such as backup supply for droughts and special industrial uses.

Studies could be carried out to evaluate the practicability of artificial recharge, urbanization effects on ground water, and disposal wells in the saline aquifers. Construction and use of analog, digital, or hybrid models would facilitate these studies and additional water-related stresses on the system.

INTRODUCTION

Ground water once supplied much of the water requirements of the San Juan area. With the completion of the Lago Lofza reservoir in 1953, surface water gradually replaced ground water as a source of supply. It was not until the severe droughts of the mid-1960's when inflow to the Lago Lofza declined to near zero that the vulnerability of surface-water sources was realized. An emergency drilling program developed sufficient ground-water supplies to supplement surface-water supplies and meet the needs of the metropolitan area.

A post-drought analysis of the sources of water supply for the metropolitan area indicated a need for better knowledge of the ground-water resources. A study was implemented through the cooperative water-resources investigation program between Commonwealth agencies of Puerto Rico and the U.S. Geological Survey.

The metropolitan area (fig. 1) includes the capital city of San Juan and all or part of the municipalities of Carolina, Bayamón, Cataño, Guaynabo, Dorado, Río Piedras, and Toa Alta. The study area extends from the Río Grande de Loíza on the east to the Río de la Plata on the west, and from lat 18° 22' N, which approximately parallels the volcanic-sedimentary rock contact, north to the Oceano Atlantico. For purpose of reference, the metropolitan area has been arbitrarily divided into three units--Bayamón, San Juan, and Carolina (as shown in fig. 1).

GEOGRAPHY

Physical Setting

The metropolitan San Juan area lies in the Northern Coastal Lowland and Northern Foothills physiographic regions (Picó, 1950). The Northern Coastal Lowland is a plain about 5 mi (8 km) in width, that slopes gently from the sea to the foothills. The plain has been built up by surficial deposits consisting of sand, silt, clay, and muck overlying a dissected older surface, the remnants of which stand above the plain as isolated mogotes or hills. Many of the mogotes rise more than 300 ft (90 m) above sea level and 200 ft (60 m) or more above the coastal plain.

A nearly continuous line of marshes, mangrove swamps, and lagoons lie just inland of the shoreline. The lagoons, including Bahía de San Juan, are joined by channels. Direct access of the lagoons to the sea is poor and circulation of water is sluggish.

The Northern Foothills characteristically are rounded hills, many attaining an altitude of 1,000 ft (300 m) and some as much as 2,000 ft (600 m). The hills are composed chiefly of sandstone and siltstone, associated volcanic and intrusive rocks, and some limestone. Streams rising in the interior uplands pass through the foothills in narrow valleys whose flood plains are flanked by alluvial terraces.

Major rivers bounding or passing through the study area are, from east to west; the Río Grande de Loíza, Río Piedras, Río de Bayamón, and Río de la Plata. The Río Piedras empties into Bahía de San Juan; whereas, the other rivers discharge directly to the sea.

Population and Economic Situation

Puerto Rico in general, and San Juan in particular, have experienced probably one of the

fastest economic growth rates in the world in the past 25 years. The Commonwealth has grown at a rate comparable to Israel and Japan and about twice that of the continental United States--more than 10 percent per annum.

The population of the San Juan metropolitan area has grown 26 percent from 1950 to 1960 to 647,979 inhabitants; and 31 percent from 1960 to 1970 to 851,247 inhabitants. Almost one third of all the inhabitants on the island live in the San Juan metropolitan area. The trend in population is outward to the suburban areas as transportation, housing, and living standards improve, and as the urban center becomes more commercialized.

The industries in and around San Juan are similar to those of other large cities. The leading types of commercial establishments are food products, tobaccos, textiles and clothing, furniture and wood products, printing, chemicals, cement, metal fabrication, machinery and electrical equipment, glass, petroleum refineries, rum distilleries and breweries. Although the island's rate of unemployment is high, more than 12 percent (1970), the rate in San Juan is comparable to the continental United States average of 6 percent.

Climate

The climate in San Juan is tropical marine. Air temperature at the National Weather Service station, in Old San Juan, ranges from an average of 27.2° C in August to 23.9° C in January.

Throughout Puerto Rico rainfall increases inland toward the mountains. In the San Juan metropolitan area, the average annual rainfall ranges from 60 in (1,520 mm) on the coast to 80 in (2,030 mm) 5 mi (8 km) inland. Rainfall is seasonal with a rainy period from July through October (the hurricane season) and a secondary wet period in May. The dry season occurs between January and April. In an average year, there are 209 days of measurable precipitation in Old San Juan.

Figure 2 shows the long-term annual rainfall at Río Piedras and Old San Juan. Wet and dry periods are evident from the 5-year moving average. Of particular prominence are the severe droughts of the 1920's, 1930's and 1960's.

Pan evaporation measured at the Old San Juan weather station exceeds rainfall by about 20 in (508 mm) a year. The average annual evaporation measured over 4 decades is 82 in (2,080 mm) with an average monthly high of 8.04 in (204 mm) in March and a low of 4.48 in (114 mm) in December. A short distance inland at Río Piedras, however, the rainfall, 74.2 in (1,880 mm), exceeds the pan evaporation, 72.4 in (1,840 mm).

In Puerto Rico the prevailing trade wind is from the east or the north-northeast; however, from September to November there is an alternating of wind currents from the south and the southeast. In addition, there are breezes caused by the differential heating of the land and the sea--during the day the breeze is from the sea to land, but at night it is reversed.

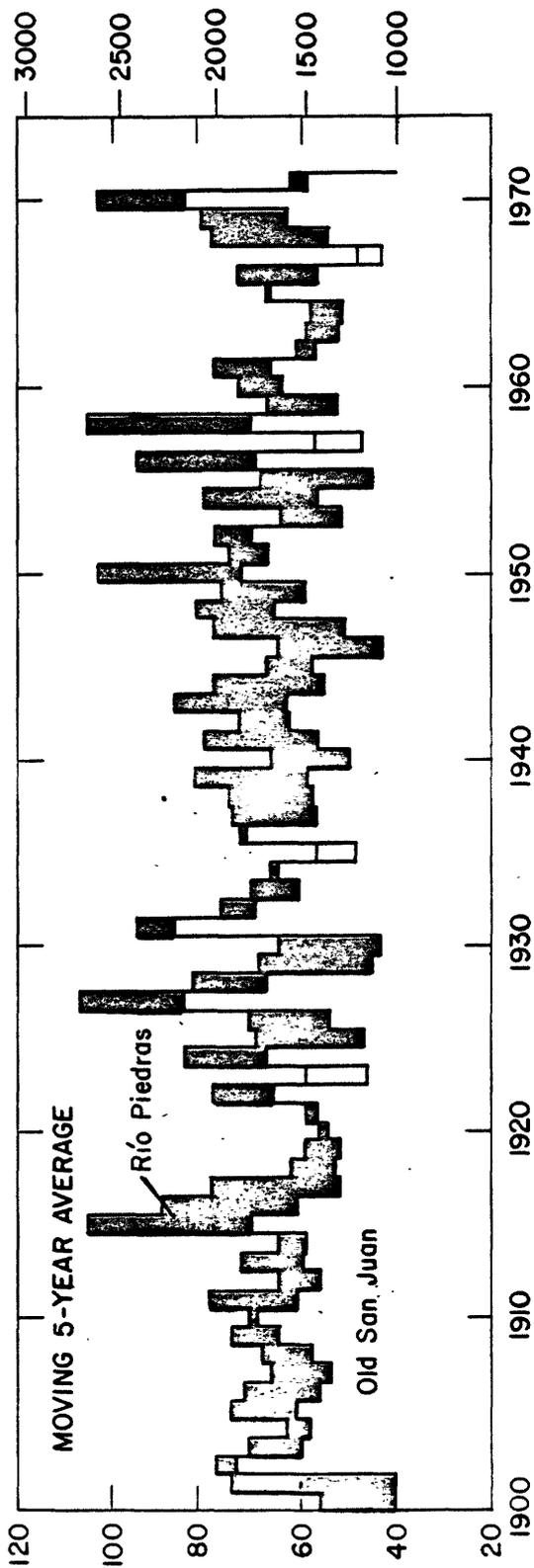
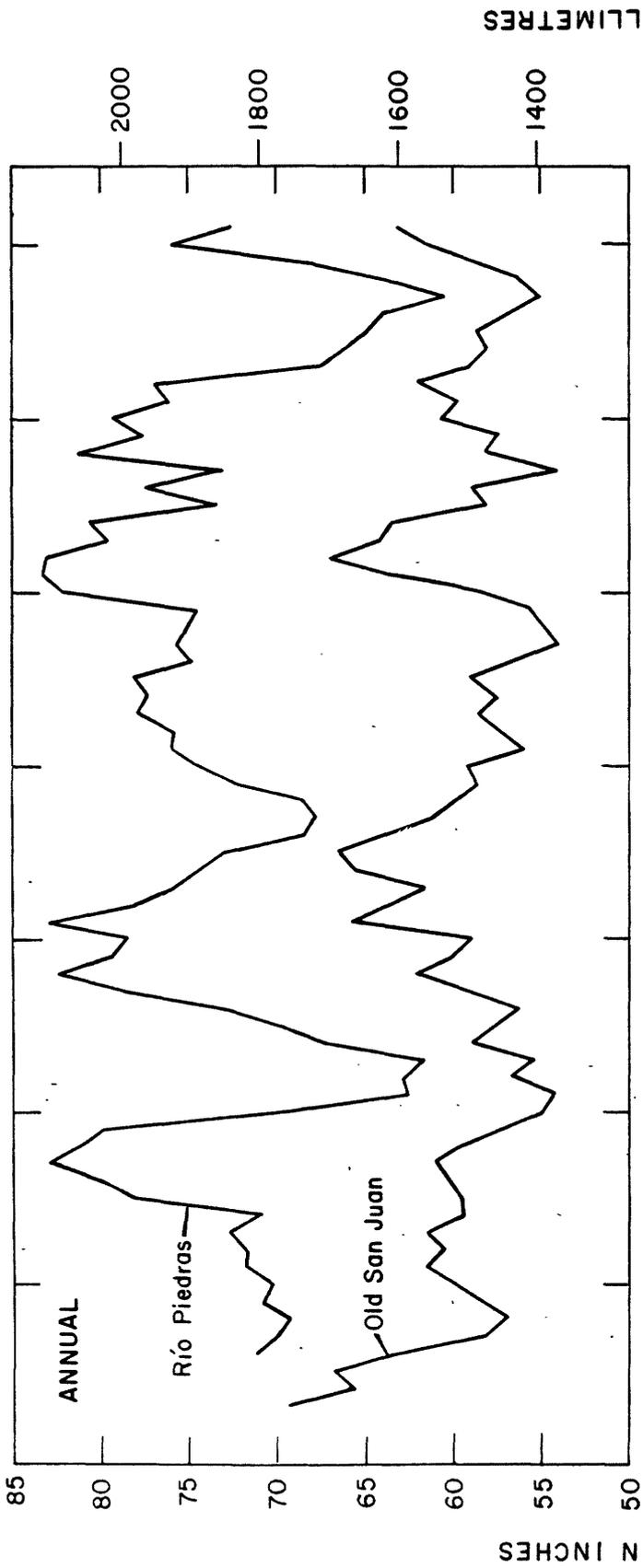


Figure 2.--Annual and moving 5-year average rainfall of Río Piedras and Old San Juan rain gages, 1900-71 (data from U.S. National Oceanic and Atmospheric Administration).

Hurricanes commonly originate in the Caribbean but only six storms of hurricane intensity have affected San Juan in the past 60 years.

Water Use and Municipal Supply

Before 1953, San Juan obtained its water supply from a combination of surface water from the Río Piedras and the Río de Bayamón, and ground water from several high-yield wells. Apart from the municipal supply, many installations in San Juan, such as the Ft. Buchanan military complex, maintained their own wells. With the completion of the Lago Lofza reservoir in 1953, many of the well systems were abandoned and water was obtained from the municipal supply system. Ground-water pumpage declined from 5×10^6 gal/day ($0.22 \text{ m}^3/\text{s}$) in 1945 to 3×10^6 gal/day ($0.13 \text{ m}^3/\text{s}$) in 1960.

In fiscal year 1971 (July 1970–June 1971), the output of municipal water supply in metropolitan San Juan averaged about 108×10^6 gal/day ($4.7 \text{ m}^3/\text{s}$), double the 54×10^6 gal/day ($2.4 \text{ m}^3/\text{s}$) in fiscal year 1959. The water consumed or paid for in fiscal year 1971 was about 80×10^6 gal/day ($3.5 \text{ m}^3/\text{s}$) indicating a water loss, apparently through leaky mains, of about 25 percent.

GEOLOGY

The rocks of the San Juan area are classified for the purpose of convenience as volcanic rocks, sedimentary rocks, and surficial deposits. Needless to say, there are large variations in rock type in each group. The areal extent of these rocks in the San Juan area is shown in the hydrogeologic map (fig. 3).

Volcanic Rocks

Volcanic tuff, breccia and lava; associated sandstone, siltstone and limestone; and some intrusive rocks of Cretaceous and Tertiary age are found in the Northern Foothill region south of San Juan. Folding, faulting and metamorphism have destroyed many of the original physical characteristics of these rocks, such as solution limestone, porous tops in lava flows, and open-pore space in sandstones. Common to these rocks is a general lack of permeability, except in a weathered and fractured surficial zone as much as several hundred feet thick that follows the general topography.

Sedimentary Rocks

Sedimentary rocks of Tertiary age underlie the Northern Coastal Lowland region. The formations are composed of consolidated gravel, sand, and clay and calcareous rocks ranging from marl to indurated limestones. They have a roughly east-west strike and dip 4 to 6 degrees seaward. Some high-angle normal faulting is evident; however, displacement is small and does not seem to be significant.

Production, distribution, capacity, plant, system, and source of water supply in fiscal year 1971

Plant ^{1/}	Capacity million gal per day (cubic metres per second)	Production million gal per day (cubic metres per second)	Source	Distribution	System
Sergio Cuevas	60 (2.6)	67.5 (3.0)	Lago Lofza ^{2/}	Carolina-San Juan area and 10 x 10 ⁶ gal (38,000 m ³) underground storage tank	Lofza
Guaynabo	26 (1.1)	29.7 (1.3)	Lago de Cidra ^{3/} Rfo de Bayamón Rfo Guaynabo	Guaynabo-Bayamón area and 2 storage tanks 10 x 1.0 ⁶ gal (38,000 m ³)	Bayamón
Univ. of P.R. Experiment Station, Rfo Piedras	2.5 (0.11)	2.2 (0.10)	Lago Las Curias ^{4/}	Rfo Piedras-San Juan area	Rfo Piedras
San Juan	10.7 (0.47)	0.2 (0.01)	18 wells	San Juan area	Hato Rey
Campanilla- Sabana Seca	15.6 (0.68)	8.88 (0.39)	16 wells	Levittown area	Levittown

^{1/} See figure 1 for location.

^{2/} 6.5 billion gal (24.6 hm³) storage reservoir.

^{3/} 1.7 billion gal (6.43 hm³) storage reservoir.

^{4/} 367 million gal (1.39 hm³) storage reservoir.

These formations are best exposed in the west and inland parts of the study area. They are overlain by surficial deposits near the sea and in the eastern part of the study area.

The rocks can be separated into four recognizable formations. In order from oldest to youngest, they are: San Sebastián Formation, Cibao Formation, Aguada Limestone, and Aymamón Limestone.

San Sebastián Formation

The San Sebastián Formation of Oligocene age is composed of crossbedded to massive beds of sand, sand and gravel, and sandy clay; with some thin beds of sandstone and sandy limestone. The formation can be considered to be consolidated but is essentially uncemented. The outcrop area and the configuration of the top of the San Sebastián are shown in figure 4. The formation attains its maximum thickness of about 500 ft (150 m) in the western part of the study area, but Pease (1968) attributes 150 ft (45 m) of this thickness to the Mucarabones Sand, a formation overlying the San Sebastián and grading into the Cibao. In this report the Mucarabones Sand, as mapped by Pease (1968), is included in the San Sebastián. However, recent work in the Bayamón quadrangle by Monroe (1973) indicates that the Mucarabones Sand intertongues eastward with the entire lower part of the overlying Cibao Formation; so that the age of the Mucarabones Sand is Oligocene and Miocene. The San Sebastián Formation commonly is 165 to 330 ft (50 to 100 m) thick, becoming progressively thinner to the east.

In the vicinity of Carolina, the San Sebastián either pinches out or the remnants become indistinguishable from the overlying Cibao Formation.

Cibao Formation

The Cibao Formation (fig. 3) is of Oligocene and Miocene age and conformably overlies the San Sebastián Formation. The Cibao is composed of interbedded marl, limestone, clay, sand and gravel. It attains its maximum thickness of 380 ft (115 m) in the westernmost part of the study area, thinning eastward to about 130 ft (40 m) thick in the vicinity of Carolina.

In the westernmost part of the study area, the Cibao has been divided into five members (Monroe and Pease, 1962):

1. Upper member--chalk, sandy limestone and sandy marl; 100 to 160 ft (30 to 50 m) thick.

2. Miranda Sand Member--sand and gravel, filling channels cut into the underlying limestone; 0 to 60 ft (0 to 20 m) thick.

3. Quebrada Arenas Limestone Member--consists of alternating beds less than 3 ft (1 m) thick, of dense crystalline limestone and soft marly limestone; 0 to 70 ft (0 to 20 m) thick.

4. Rfo Indio Limestone Member--a yellowish-orange earthy limestone that grades into a sandy marl toward the east; reported to be 230 ft (70 m) maximum thickness.

5. Lowermost member (unnamed)--consists of sandy limestone and marl facies transitional with the San Sebastián; 100 to 230 ft (30 to 70 m) thick.

The three middle members apparently crop out only in the Rfo Bucarabones Valley (section A-A', fig. 3). The upper and lowermost members are identifiable in the vicinity of the Rfo de Bayamón (section B-B', fig. 3).

In the San Juan and Carolina areas, the Cibao has not been officially divided into members; consequently, the formation is described as one geologic unit (section C-C' and D-D', fig. 3).

In the Carolina area, the Cibao overlaps the San Sebastián and is believed to rest directly on the bedrock formations of tuff and volcanic rocks. Here the formation is about 130 ft (40 m) thick.

In places the Cibao forms topographic ridges but more commonly makes up the lower slopes of hills and mogotes capped by the more resistant Aguada and Aymamón Limestones. In the San Juan area exposures of the Cibao are evident at the base of Montes San Patricio, Montes de Canejas, and the smaller hills south of the San José Lagoon. Figure 5 is an outcrop map of the Cibao Formation showing structure contours on the top of the formation.

Aguada Limestone

The Aguada Limestone of Miocene age is a transitional formation between the Cibao marl and the relatively pure crystalline limestone of the overlying Aymamón Limestone (fig. 3). Briggs and Akers (1965) described the Aguada on the north coast as "hard, thick-bedded to massive calcarenite and dense limestone interbedded with chalky limestone and marl; commonly containing some quartz grains and locally thin-bedded near top." It ranges in thickness from 100 to 250 ft (30 to 75 m) in outcrop in the study area. South of the Bahía de San Juan, the hard crystalline beds occur in the upper part while the softer and marly beds predominate in the lower part (Gelabert, 1964).

The Aguada is a ridge former and together with the Aymamón Limestone makes up most of the mogotes in the San Juan area. Except for these last remaining vestiges of the great karst region to the west, the limestones in San Juan have been largely eroded away and covered with alluvial clay, sand, and beach deposits.

Aymamón Limestone

The uppermost limestone, the Aymamón of Miocene age, is exposed as case-hardened caps on a few hilltops in Montes de Canejas and in the small hills around the juncture of

Caño Martín Peña and the Laguna San José (fig. 3). Elsewhere it lies beneath a mantle of alluvium and other surficial deposits. The following description of the formation is given by Zapp, Bergquist, and Thomas (1948), "It consists almost entirely of very dense conchoidally fracturing limestone of white, light gray, buff and rose colors; unit is quite uniform over its entire outcrop and throughout its entire thickness." The map by Monroe and Pease (1962) of the Bayamón quadrangle shows the limestone outcrops, both of the Aguada and Aymamón to be quite extensive, forming the tops of many of the haystack hills. In the Bayamón area the Aymamón is either pink or white, well indurated, usually dense limestone, 215 ft (65 m) thick were exposed. Kaye (1959) estimates the thickness of the Aymamón to be as much as 2,000 ft (600 m) at the coastline. Geophysical studies at Palo Seco indicate an aggregate thickness of middle Tertiary limestones (Aguada and Aymamón) to be about 3,000 ft (900 m).

Surficial Deposits

A variety of alluvial, terrace, blanket sand, beach, and dune deposits ranging in age from Miocene to Holocene mantles the bedrock over much of the study area. Terrace and blanket sand deposits are sometimes referred to as old alluvium, and form a veneer of red to white silty clay, sand and clay, and sand over the older formations. The thickness of these deposits may be more than 100 ft (30 m) in San Juan (fig. 6).

A blanket of loosely cemented dune sand of Pleistocene age overlies the Santurce and Old San Juan areas. The dune sand is composed of quartz and calcite grains, cemented in a calcite matrix. The Holocene deposits include beach sand, swamp and lagoon mud, and recent alluvium or flood-plain deposits of the existing river systems.

HYDROLOGY

Rainfall on the inland mountain slopes drains into four main catchment areas--Río Grande de Loíza, Río Piedras, Río de Bayamón, and Río de la Plata (fig. 1). For the most part, these basins lie on relatively impervious volcanic rock; runoff is rapid, commonly resulting in flash flooding in the lower urbanized reaches of the streams.

Water infiltrating the volcanic rock flows largely through the weathered zone and then into stream valleys. Some ground-water flow through the volcanic rock may ultimately recharge the Tertiary sand and limestone aquifers.

The sand and limestone aquifers of the coastal plain are the principal water-bearing formations in the San Juan area. Recharge to these formations is principally on their outcrops by rainfall and infiltration of streamflow, and discharge is principally into swamps and lagoons along the coastline. Discharge from the confined zones of these aquifers probably is by vertical leakage to the overlying formations.

A possible secondary source of recharge to the aquifer in urbanized areas is leaky water and sewer lines.

In the following section of the report, the terms specific capacity, transmissivity, and hydraulic conductivity will be used in reference to the hydraulic properties of the aquifers. Specific capacity, expressed in gallons per minute per foot of drawdown or cubic metres per second per metre of drawdown is, as the units indicate, the yield of a well divided by the difference between the nonpumping and pumping water level (drawdown) in a well for a time period. The duration of discharge in this report is for a period of 8 hours. Hydraulic conductivity (formerly referred to as coefficient of permeability) is the volume of water that will pass through 1 ft² (1 m²) of an aquifer in 1 day; whereas, transmissivity is the volume of water that will pass through a 1-ft (1-m) wide vertical section, the full thickness of an aquifer in 1 day. Hydraulic conductivity is expressed in (ft³/day)/ft² [cubic feet per day per square foot] or ft/day [feet per day]. Transmissivity is expressed as (ft³/day)/ft [cubic feet per day per foot] or ft²/day [feet squared per day]. In metric terms, hydraulic conductivity is expressed as (m³/day)/m² [cubic metres per day per square metre] or m/day [metres per day], and transmissivity is (m³/day)/m [cubic metres per day per metre] or m²/day [square metres per day].

Wells in the metropolitan area are often perforated the entire length of their casings. Consequently, wells starting in the unconfined aquifers may be completed in the confined aquifers and tap both zones. Composite yields and water levels commonly result. Often the yield of a well is controlled to a large degree by the most permeable aquifer tapped, and the water level in a well may be higher or lower than that in the unconfined aquifer owing to the head effects of the lower confined aquifer. Consequently, direct use of well data to describe well performance and aquifer characteristics can be misleading. Variations in transmissivity of the coastal aquifers shown in figure 3 are primarily a composite of the transmissivity of the various water-bearing units.

Ground-Water Levels

Altitudes of the water surface in the volcanic and sedimentary rock unconfined aquifers and of the potentiometric surface of the confined zones of the sedimentary rock aquifers are shown in figure 7. The water surface in the volcanic rocks reflects the control exerted by surface drainage features with ground-water discharge being primarily to streams. But it also shows that in interbasin areas there is some ground-water discharge from the volcanic rocks directly to the sedimentary rocks as indicated in the Montes de Hatillo area, south of Hato Rey. Ground-water levels in the unconfined aquifers of the sedimentary rock also show control exerted by surface-drainage features along the major rivers. The potentiometric surface of the confined zones of the aquifer, in contrast, reflects the head created by the ground-water levels in the recharge area and friction losses in the aquifer.

Observations of the ground-water levels (fig. 8) show that recharge generally occurs during the rainy season from August through November, with a secondary recharge period in April or May. Recharge, however, can occur at any time of the year as the result of major rainstorms.

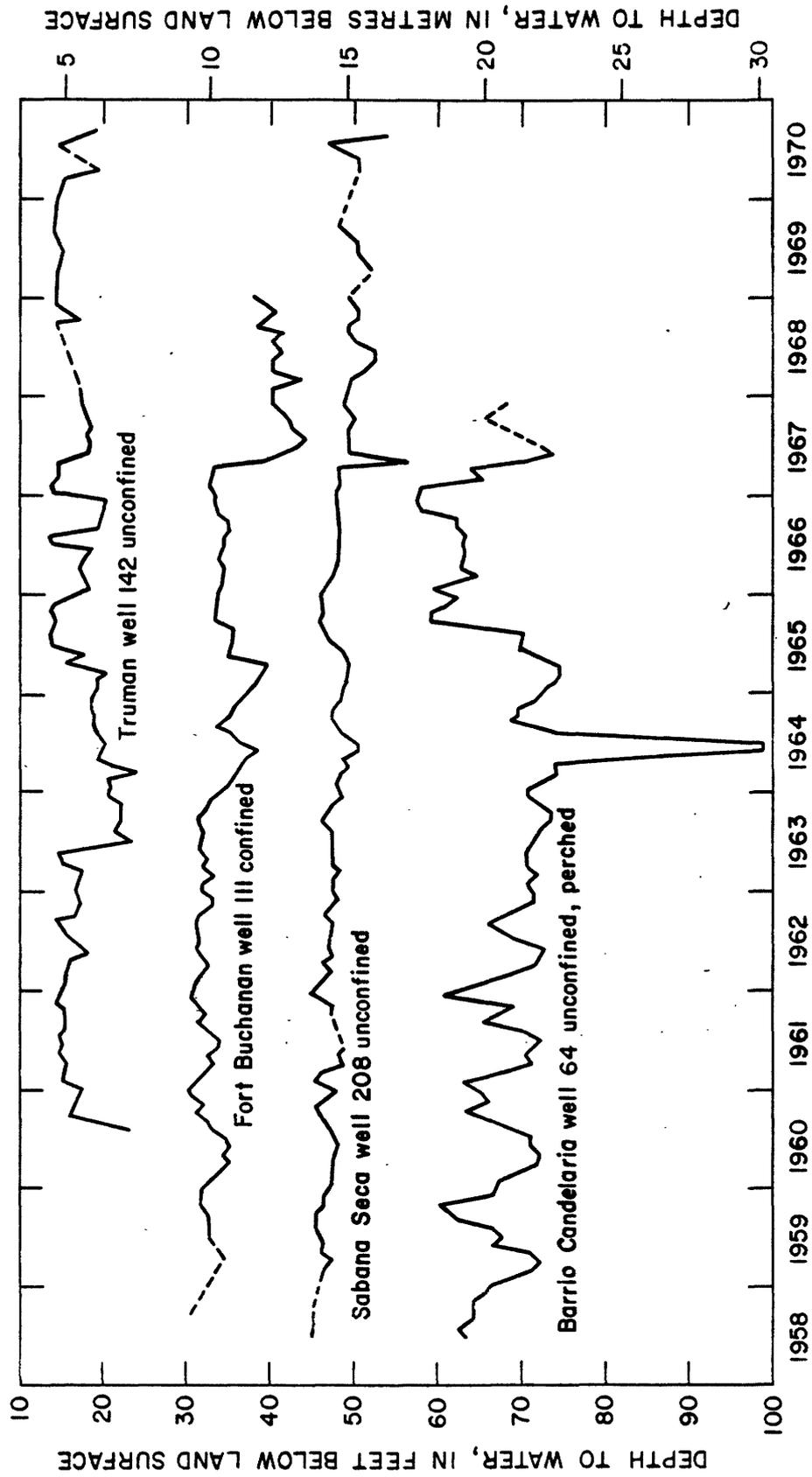


Figure 8.--Hydrographs of selected wells in the San Juan area.

Water-level fluctuations reflect the hydraulic characteristics of the aquifers. The Candelaria well 64 (fig. 8) is situated on the high plateau west of Bayamón, the recharge area for Tertiary formations in the Bayamón area. The wide fluctuation of the water levels in the well indicates the generally low permeability and porosity of the Cibao Formation. A water-level high of 58 ft (18 m) below land surface was reached in late 1966, following several successive wet years. The low water level of record was 99 ft (30 m) below land surface in mid-1964, in response to the dry years of 1963-64. Ordinarily there is about a 10-ft (3-m) variation between the high-water levels in the rainy season and the low levels in the dry season in this well.

The Truman well 142 (fig. 8), along with a number of other Puerto Rico Aqueduct and Sewer Authority wells in San Juan, is used to supplement municipal supply during dry periods when surface-water storage is low. Measurements were taken in the Truman well, both under nonpumping and pumping conditions. The well shows only very modest changes in water level from a high of 13 ft (4.0 m) to a low of 24 ft (7.3 m) below land surface. The low level was primarily a reaction to the drought of 1963-64, when the well was being pumped continuously. Because of the high permeability and storage of the limestone, a more constant water level is sustained during adverse conditions than in the less permeable Cibao and San Sebastián Formations.

Recharge

The average annual recharge to an aquifer or aquifer system determines the long-term yield that can be obtained without depletion or other damage to the aquifer. Recharge usually occurs on the outcrop surface of the aquifer either from the infiltration of rainfall or from surface water from streams that flow across the outcrop. Occasionally recharge will be from underlying or overlying water-bearing formations.

Rainfall is usually the principal source of recharge. Even then a combination of certain conditions must occur before recharge will result. Rainfall must be sufficient to overcome soil moisture demands and yet be of low intensity for maximum infiltration to occur. As these conditions are usually reached only during the rainy season, recharge is cyclic.

The condition of the outcrop area that receives recharge is also critical--the surface must be permeable. Throughout metropolitan San Juan, the recharge areas of the aquifers are being urbanized. High-density housing, streets, and other impervious surfaces are or will greatly impair the receptivity of the recharge areas of the aquifers.

The principal recharge areas in the Bayamón area are the high plateau or ridge of Aguada and Aymamón Limestones lying on top of the Cibao Formation and the outcrop area of the Cibao and San Sebastián Formations to the south (figs. 3, 4, and 5). Important to the recharge on the plateau and the area to the south are the large areas of blanket sand forming an absorbent surface through which rainfall can percolate to the underlying limestone and sandstone. Water infiltrating the ridge flows either northward through the Aguada Limestone or downward through the Cibao Formation and south to the San Sebastián Formation (see fig. 3, section A-A').

In the San Juan-Carolina area, recharge to the San Sebastián Formation is derived from rainfall on the outcrop area, in places mantled by alluvium, from flow losses from the Río Piedras in the intake area, and from underflow through the weathered zone in the volcanic rocks of Montes de Hatillo. Recharge to the Cibao Formation, to the Aguada Limestone, and to Aymamón Limestone is primarily from rainfall on the outcrop area of the Cibao, by percolation through the alluvium mantling these formations, and to a lesser extent through isolated limestone mogotes.

Within the Carolina area, a mogote ridge, Cerro San José (fig. 3, section D-D') is a source of recharge to the limestone and possibly to the underlying sand aquifer of the Cibao Formation. The water-table map (fig. 7) indicates a low swell in this area that may indicate the contribution of local recharge.

Recharge to the aquifers of the metropolitan area is undoubtedly being reduced by extensive urbanization of the intake areas. It is possible that much of the natural recharge that has been lost because of roads, housing, and other impervious structures is being made up by leakage from water and sewage mains. The 28×10^6 gal/day ($1.2 \text{ m}^3/\text{s}$) unaccounted loss from the metropolitan distribution system lends credence to this possibility.

Volcanic Rocks

The bedrock aquifer consists of consolidated rocks principally of marine volcanic origin. These include siltstone, tuff, breccia, andesite, and limestone of Cretaceous and early Tertiary age. Usually these rocks are fine grained and tightly compacted and do not yield water freely to wells. Water that is available flows through cracks, fractures, and bedding planes in the weathered zone of the bedrock. In general, the water-bearing zone is a surficial mantle as much as 300 ft (90 m) thick.

Wells producing from the bedrock aquifer are chiefly in the eastern half of the metropolitan area tapping Tertiary-Cretaceous siltstone underlying the Montes de Hatillo and the Carolina area. The average yield of 25 wells is 52 gal/min (3.3 l/s) with a maximum yield of 300 gal/min (19 l/s). Specific capacities of wells averaged 1.4 (gal/min)/ft [2.9 (l/s)/m] of drawdown. No wells are known to tap the Cretaceous limestone in the Carolina area; however, modest yields possibly could be derived from this formation if metamorphism has not destroyed the original porosity or if secondary solution openings have developed.

Sedimentary Rocks and Surficial Deposits

The Tertiary sedimentary rocks comprise the principal aquifers of the coastal lowlands. Water-bearing units in these rocks range in composition from sand and gravel to nearly pure limestone.

Quaternary sediments predominately of alluvial origin, mantle the Tertiary rocks throughout much of the area. Clay and silt are the principal constituents of these deposits in the coastal areas, but inland in association with the mogotes of Tertiary rocks are high-level

terrace deposits commonly referred to as blanket sands. Water-bearing sand and gravel lenses are often found in the valley alluvium deposited by present-day rivers.

The water-bearing units of all the formations are hydraulically interconnected to some degree. The San Sebastián Formation and the lower part of the Cibao Formation are water-table aquifers in their recharge areas but become artesian seaward. The upper part of the Cibao Formation, the Aguada and Aymamón Limestones, and the Quaternary sediments are water-table aquifers.

San Sebastián Formation

In the past years, the San Sebastián Formation was not recognized as a major aquifer in the metropolitan area. Reexamination of well records, however, shows that many wells formerly assigned to the alluvial aquifer actually tap the San Sebastián Formation. In the metropolitan area, the San Sebastián is comprised predominantly of sand and some gravel with local limestone lenses--a sharp contrast to the typical gravelly clay that comprises the formation farther to the west.

In the outcrop area, ground water in the San Sebastián and basal Cibao is unconfined. DOWNDIP (seaward), however, clay zones in the middle part of the Cibao form a confining layer creating confined conditions in the underlying rocks. From the vicinity of the Río de Bayamón east, it is possible that the clayey alluvium overlying the San Sebastián and Cibao Formations also acts as a confining layer. That this is the case becomes more plausible when it is considered that the Cibao Formation is predominantly a sand in the San Juan-Carolina area and the confining clay zone in the middle of the Cibao is generally missing.

Yield of wells tapping the San Sebastián Formation--Mucarabones Sand is low to moderate. Well yields range from 13 to 800 gal/min (0.8 to 50 l/s), with an average of 244 gal/min (15.4 l/s). Many wells have been abandoned because of low yield, particularly those located near the featheredge of the formation's southernmost outcrop. The specific capacities of wells are modest and average 3.1 (gal/min)/ft [0.64 (l/s)/m] of drawdown.

Cibao Formation

Of the formations containing fresh water in the western part of the metropolitan area, the Cibao is the thickest; yet it has the least favorable water-bearing properties largely because of the clayey nature of the formation. There are, however, horizons of limestone and sand that contribute appreciable quantities of water to wells. The limestone horizons in the upper part of the Cibao Formation merge with the unconfined aquifer of the San Sebastián Formation. Between these water-bearing units is an ill-defined section of clay or clay lenses that acts as a confining layer.

The Cibao Formation thins in the eastern part of the metropolitan area and the clay confining layer between the upper and lower members of the formation essentially disappears.

The Cibao Formation can be considered to be a transition formation between the sandy San Sebastián Formation and the relatively pure Aguada and Aymamón Limestones. As such it is part of both water-bearing units.

Throughout much of the metropolitan area, it is often difficult to determine from which unit a well in the Cibao is obtaining its water.

In the Bayamón area, wells in the Cibao Formation are located along Highway 2 on the plateau-like ridge which is also a major recharge area for this formation. Practically all the wells have low yields, low specific capacities, and a diversity of water levels. Wells along the ridge often tap the shallow water-bearing zones perched in limestone overlying the clay horizon and a deeper water-bearing zone in the lower marl of the Cibao. For example, in well 118 (fig. 3) water cascaded from the perched zone to lower levels of the ground-water surface 280 ft (85 m) below. To make the well useful, it was backfilled to within 80 ft (24 m) of the surface to tap the perched water.

Other examples of the water levels in wells becoming lower with depth are evident on the Bayamón ridge. Well 87 (fig. 3), a shallow well, has a water level of 5 ft (1.5 m) below land surface, and a deep well nearby (well 91) has a water level of nearly 100 ft (30 m) below land surface. In the same general area an 80-ft (24-m) well (well 66) has a water level of 56 ft (17 m) and a 130-ft (40-m) well (well 75) has a water level of 126 ft (38 m). The differences can be explained in section A-A' (fig. 3) by imagining that the deeper wells intersect surfaces of lower head that emerge on the sides of the water-table mound. Shallow wells, on the other hand, intersect potential lines of higher head found near the top of the mound.

Wells in the report area tapping the Cibao Formation give a wide range in yield: 0 to 510 gal/min (0 to 32 l/s), but average only 120 gal/min (8 l/s). Specific capacities of wells are low, averaging 3.1 (gal/min)/ft [0.64 (l/s)/m] of drawdown for 24 wells. A water-level recovery test run on a well in San Juan gave a transmissivity of 160 ft²/day (15 m²/day) indicating properties of a confining bed rather than an aquifer.

Aguada Limestone

The Aguada Limestone attains its permeability and porosity from solution openings in the rock. In the course of geologic time, percolating ground water has dissolved the soluble material leaving openings from the size of capillaries to huge caverns, often crosscut by solution pipes or fracture crevices. Generally the average texture of these solution openings in the Aguada is from finger to fist size, not large enough for subterranean rivers but capable of supporting large yields to wells. Many large caverns and vertical pipes, carved during and before the Pleistocene age, are now filled with clay and sand plugs which actually tend to reduce porosity. Most of these plugs appear to be above the water table and may not affect the water-bearing capacity of the saturated zone. The average yield from 50 wells is 540 gal/min (34 l/s).

Aymamón Limestone

The Aymamón Limestone is similar to the Aguada Limestone but contains salt water throughout most of the metropolitan area. The lower part of the Aymamón is slightly less permeable than the Aguada, but scattered well data indicate the upper part of the Aymamón is more permeable. The average yield of the Aymamón to 21 wells is 455 gal/min (29 l/s). The upper part of the Aymamón along the coast yields as much as 2,000 gal/min (130 l/s) of salt water.

Artesian Aquifer

The San Sebastián Formation and the basal part of the Cibao Formation comprise a single water-bearing unit that in much of the metropolitan area is a confined aquifer. These formations are distinctive in the Bayamón area but tend to grade into each other to the east.

Aquifer Hydraulics

The transmissivity of the aquifer, largely computed from specific-capacity data, varies from less than 150 to 2,000 ft²/day (14 to 185 m²/day). The transmissivity and storage coefficient from well 89 at the foot of Montes de San Patricio are typical of the aquifer. An aquifer test (Unklesbay, 1945) yielded a transmissivity of 1,000 ft²/day (93 m²/day) and a storage coefficient of 1.3×10^{-4} indicative of confined conditions. The well was pumped for 26 hours at an average rate of 400 gal/min (25 l/s).

An estimate of ground-water flow through the aquifer can be made using the formula

$$Q = TIL$$

- where: Q = quantity in cubic feet per day (cubic metres per second)
T = transmissivity in square feet per day (square metres per day)
I = gradient of potentiometric surface in feet per foot (metres per metre)
L = width of aquifer under consideration in feet (metres).

Using the data from the above aquifer test as representative of the transmissivity of the confined aquifer and the potentiometric gradient in the vicinity of Montes de San Patricio, then

$$Q = 1,000 \text{ ft}^2/\text{day} \times \frac{43 \text{ ft}}{5,280 \text{ ft}} \times 5,280 \text{ ft}$$

$$Q = 43,000 \text{ ft}^3/\text{day} [322,000 \text{ gal}/\text{day}] \text{ flow per mile width of aquifer parallel to the coast, or in metric terms } 760 \text{ (m}^3/\text{day)/km.}$$

The intake area of the artesian aquifer covers approximately 15 mi² (39 km²). Average daily recharge derived principally from rainfall is estimated at 0.75 (10⁶ gal/day)/mi² [1,100 (m³/day)/km²] of outcrop area--a total of about 11 x 10⁶ gal/day (42,000 m³/day) or 20 percent of the average rainfall, 52 x 10⁶ gal/day (197,000 m³/day). If recharge is

evenly distributed over the 38 mi² (98 km²) of the coastal plain believed to be underlain by the aquifer, an estimated yield of 0.30 (10⁶ gal/day)/mi² [440 (m³/day)/km²] is available.

The potentiometric surface of the confined zone is above land surface in much of the low-lying coastal plain (fig. 7). Wells in those areas that tap this unit often flow. Known flowing wells occur in the lower valleys of the Río de Bayamón and the Río Piedras and the coastal plain south of San José Lagoon. The largest of these has a flow of 275 gal/min (17 l/s). The head in the aquifer at the well is 15 ft (5 m) above land surface. It is likely that many other wells in the low-lying areas that tap the confined zone would also flow were their castings not perforated in the overlying limestones, thus permitting water from the artesian zone to flow into the limestone.

Water-Table Aquifer

The upper part of the Cibao Formation and the Aguada and Aymamón Limestones forms a prolific unconfined aquifer. The freshwater part of the aquifer ranges from about 2 mi (3 km) in width in the Bayamón area to less than 1/2 mi (1 km) in width in the Carolina area.

Yields of 71 wells in the unconfined aquifer range from 30 to 2,500 gal/min (2 to 160 l/s) and average 510 gal/min (32 l/s). Specific capacities of wells are high, averaging 41 (gal/min)/ft [8.5 (l/s)/m] for 42 wells. In an earlier study, Bogart and others (1964) indicated an average yield of 400 gal/min (25 l/s) from 29 wells, and an average specific capacity of 53 (gal/min)/ft [1.1 (l/s)/m] from 20 wells, for the limestone aquifer. In the present study, transmissivities computed from specific-capacity data showed a range of from 7,000 to 135,000 ft²/day (650 to 12,500 m²/day) indicating the high conductivity of the aquifer. The average transmissivity computed from specific-capacity data is 13,000 ft²/day (1,200 m²/day).

The greatest production potential of the unconfined aquifer is in the Bayamón area (fig. 9) where the freshwater zone of the aquifer not only has its greatest extent but the recharge area is extensive in comparison with the areas to the east.

Two major well fields operated by the Puerto Rico Aqueduct and Sewer Authority are located in the Bayamón area (fig. 1). The Campanilla field tapping the Aguada Limestone has wells yielding as much as 1,000 gal/min (63 l/s). Average specific capacity of five wells is 63 (gal/min)/ft [13 (l/s)/m].

The Sabana Seca field taps the Aymamón Limestone and the upper part of the Aguada Limestone. Yields range from 500 to 1,000 gal/min (32 to 63 l/s) in the 10 wells in the field. During summer and fall of 1968, production from the field was 4.3 x 10⁶ gal/day (0.19 m³/s). Water quality, however, was affected by salt-water encroachment from the Río de Bayamón estuary. The wells, in an east-west line on the west bank of the estuary, showed a declining chloride concentration away from the estuary. The well nearest to the estuary had a chloride concentration of 360 mg/l (milligrams per litre). The chloride concentration of the next six wells in line progressively decreased with distance from the estuary, but all exceeded 100 mg/l.

During an aquifer test in the Sabana Seca well field, the production well (well 220, fig. 3) was pumped for 4 days at a rate of 615 gal/min (39 l/s), with a drawdown of 12.5 ft (3.8 m) and a specific capacity of 49 (gal/min)/ft [10 (l/s)/m]. Measurements made during the test showed drawdowns of less than 0.5 ft (0.15 m) in observation wells 1,000 ft (300 m) from the pumped well.

Computed transmissivity was 160,000 to 240,000 ft²/day (14,900 to 22,300 m²/day) and coefficient of storage was 0.001 (Leggette, Brashears and Graham, 1969).

Transmissivities computed from specific-capacity data on individual wells in the field are much less, 4,500 to 27,000 ft²/day (420 to 2,500 m²/day) than those computed utilizing the aquifer test. The discrepancies are attributed to well entrance losses which tend to reduce the specific-capacity values and the corresponding transmissivities. Use of properly designed wire-wound or shutter-type screens, in places of perforated casing could reduce entrance losses and thereby improve specific capacities to several hundred gallons per minute per foot of drawdown.

Static water levels in the Sabana Seca well field are from 2.9 to 5.6 ft (0.9 to 1.7 m) above sea level. Accordingly, at these levels the fresh water-salt water interface should lie at depths of 120 to 225 ft (37 to 69 m) below sea level (the depth to salt water below sea level increases approximately 40 ft [12 m] for each 1-ft [0.3-m] increase in water-table altitude above sea level). Consequently any stress put on the well field in a sustained long-term pumping effort could readily lead to a salt-water intrusion problem.

The ground-water flow through the aquifer can be estimated from the aquifer-test data computed at Sabana Seca. Using the formula: $Q = TIL$, it is found that about 600,000 ft³/day (4.5×10^6 gal/day) of ground water is moving through a 1-mi (1.6-km) wide strip of aquifer to a seaward discharge area or about 25×10^6 gal/day (1.1 m³/s) in the area between the Río de la Plata and the Río de Bayamón. Large variations in this discharge can occur when the ground-water gradient, normally about 3 ft/mi (0.6 m/km), is changed owing to tidal effects, seasonal changes in rainfall, droughts, and pumpage.

The limestone area between the Río de Bayamón and the Río de la Plata and to the divide south of Highway 2 includes about 28 mi² (73 km²). The principal drainage from the limestone is ground-water flow toward the sea and, to a lesser extent, to the main stream systems of the Río de Bayamón or the Río de la Plata. An estimated 20 mi² (52 km²) of limestone terrane containing fresh water drains toward the coast. Water-budget studies made in the Tortuguero area to the west (Bennett and Giusti, 1972) show the approximate recharge to the karst limestone, which is on the order of 1 (10⁶ gal/day)/mi² [0.02 (m³/s)/km²]. Applying this magnitude of recharge to the coastal drainage between the Río de la Plata and the Río de Bayamón, an estimated 20×10^6 gal/day (0.9 m³/s) is recharge to the aquifer as compared with approximately 25×10^6 gal/day (1.1 m³/s) discharge

computed above. At the present time, about 10×10^6 gal/day ($0.44 \text{ m}^3/\text{s}$) is pumped by wells from the aquifer, mainly in Campanilla and Sabana Seca. The current artificial draft on the aquifer is roughly half the estimated recharge rate.

In the San Juan-Carolina area, fresh water in the unconfined aquifer is found only in the upper part of the Cibao Formation and the Aguada Limestone. Well yields of more than 2,000 gal/min (130 l/s) can be obtained from the fresh-water part of the aquifer in the San Juan area; although, the yields usually are restricted to less than 200 gal/min (13 l/s) depending upon the proximity of the salt-water front. Data are too few to give a valid evaluation of the unconfined aquifer in the Carolina area. Akers (written commun., 1965) reported a well yielding 2,500 gal/min (158 l/s) of marginal-quality water (350 mg/l chloride) in the limestone, east of the Río Grande de Lofza.

Estimates of transmissivity and ground-water gradients in San Juan indicate that seaward ground-water discharge through the aquifer is on the order of 1 (10^6 gal/day)/linear mi [27 (l/s)/linear km], approximately, along the fresh-water contact. The apparent recharge area for the unconfined aquifer, however, does not appear to be extensive enough to supply the required volume of water. Recharge to the unconfined aquifer could be augmented by lateral flow from the unconfined part of vertical flow from the confined part of the San Sebastián Formation and lower part of the Cibao Formation and leaky water or sewer mains.

The Aymamón Limestone is part of the unconfined aquifer and in the San Juan-Carolina area it contains mostly salt water. Wells tapping the Aymamón near the sea yield as much as 2,000 gal/min (130 l/s) of salty water.

Surficial Deposits

The surficial deposits are not an important source of water in the San Juan area, though they do serve as a conduit for recharge to underlying aquifers. The Pleistocene eolianite deposits along the coast yield water high in chloride concentration, mainly to shallow wells. Locally, in Carolina, a few wells tap abundant supplies from Holocene alluvial deposits. Sources of fresh water, formerly described as recent alluvial deposits, are often sand and gravel deposits of the San Sebastián Formation. Examination of more than 100 driller's logs from wells in the San Juan area show the alluvial deposits to be highly clayey and relatively unfavorable for the development of wells; except possibly in some stream valleys.

Yields from several industrial wells tapping the alluvium of the Río Grande de Lofza on the eastern edge of the study area are as much as 700 gal/min (44 l/s), but they are not typical of well yields from the alluvium in the metropolitan area. Records available for 17 wells in surficial deposits show a median yield of 60 gal/min (3.8 l/s).

Surface Water-Ground Water Relationship, Río de Bayamón Basin

The base flow of streams is ground-water discharge from the adjacent aquifers. Base

flow, therefore, can be an indication of the long-term yield of an aquifer and also of the long-term average recharge to the aquifer.

An analysis of the total and base flow of the Río de Bayamón was made for different time periods, to verify, where possible, estimates of recharge and ground-water discharge determined by analyses of hydraulic data obtained from the performance of wells tapping the aquifers in the San Juan area.

The Río de Bayamón basin encompasses an area of about 95 mi² (246 km²). The river rises in the mountains about 20 mi (32 km) inland and flows northward to the sea. The upper two-thirds of its course is incised in a complex of Cretaceous age volcanic rocks, whereas the lower third flows over Tertiary age sediments and younger, predominantly Holocene age surficial deposits. The gradient of the channel changes abruptly from 95 ft/mi (18 m/km) on the volcanics to 11 ft/mi (2 m/km) on the sedimentary rocks and surficial deposits of the coastal plain.

The Río de Bayamón, as mentioned earlier, is a highly regulated stream. In August 1970, diversions from the Bayamón system were 5.56 x 10⁶ gal/day (0.24 m³/s) from the Lago de Cidra, 15.32 x 10⁶ gal/day (0.67 m³/s) from Old San Juan Dam, and 7.42 x 10⁶ gal/day (0.33 m³/s) from Santa Rosa--a total of about 28 x 10⁶ gal/day or 43 ft³/s (1.2 m³/s).

Streamflow is augmented by industrial and municipal sewage effluent discharge to the Río de Bayamón and its tributaries. In August 1970, the Guaynabo sewage treatment plant discharged an average of 2.5 x 10⁶ gal/day (0.11 m³/s) of secondary-treated sewage to the Río Guaynabo. An industrial plant on the Río Minillas and two plants on the Río Hondo had a combined disposal capacity of 1.14 x 10⁶ gal/day (0.05 m³/s). A fourth industrial plant, north of Bayamón, contributed 1.04 x 10⁶ gal/day (0.046 m³/s) of sewage to the Río de Bayamón. The total recorded contribution of sewage effluent to the Río de Bayamón in August 1970 was about 6 x 10⁶ gal/day or 9 ft³/s (0.26 m³/s).

Figure 10 shows the relationship of rainfall at Hato Tejas to discharge at the Río de Bayamón at Bayamón (station 50 0480 00) corrected for diversions. Runoff is approximately 35 percent of precipitation for the 4 years of record. Giusti and López (1967) calculated runoff as 33 percent of precipitation for 8 years of record on the adjacent Río de la Plata basin. Figure 10 also shows that evapotranspiration for a 70-in (1,780-mm) annual rainfall would be about 52 in (1,320 mm), or about double the runoff.

Figure 11 shows a series of curves corresponding to a given chance, or probability, that a certain daily discharge will be equaled or exceeded in a given month. Mean daily discharges are plotted on the vertical axis and months are represented along the horizontal axis. The curves show, in a qualitative way, the behaviour of the stream regimen in the basin and the role of ground water to streamflow.

The 90-percent curve corresponds in general to base flow and has the same variation as the seasonal fluctuation of the ground-water surface. The 1-percent curve, on the other

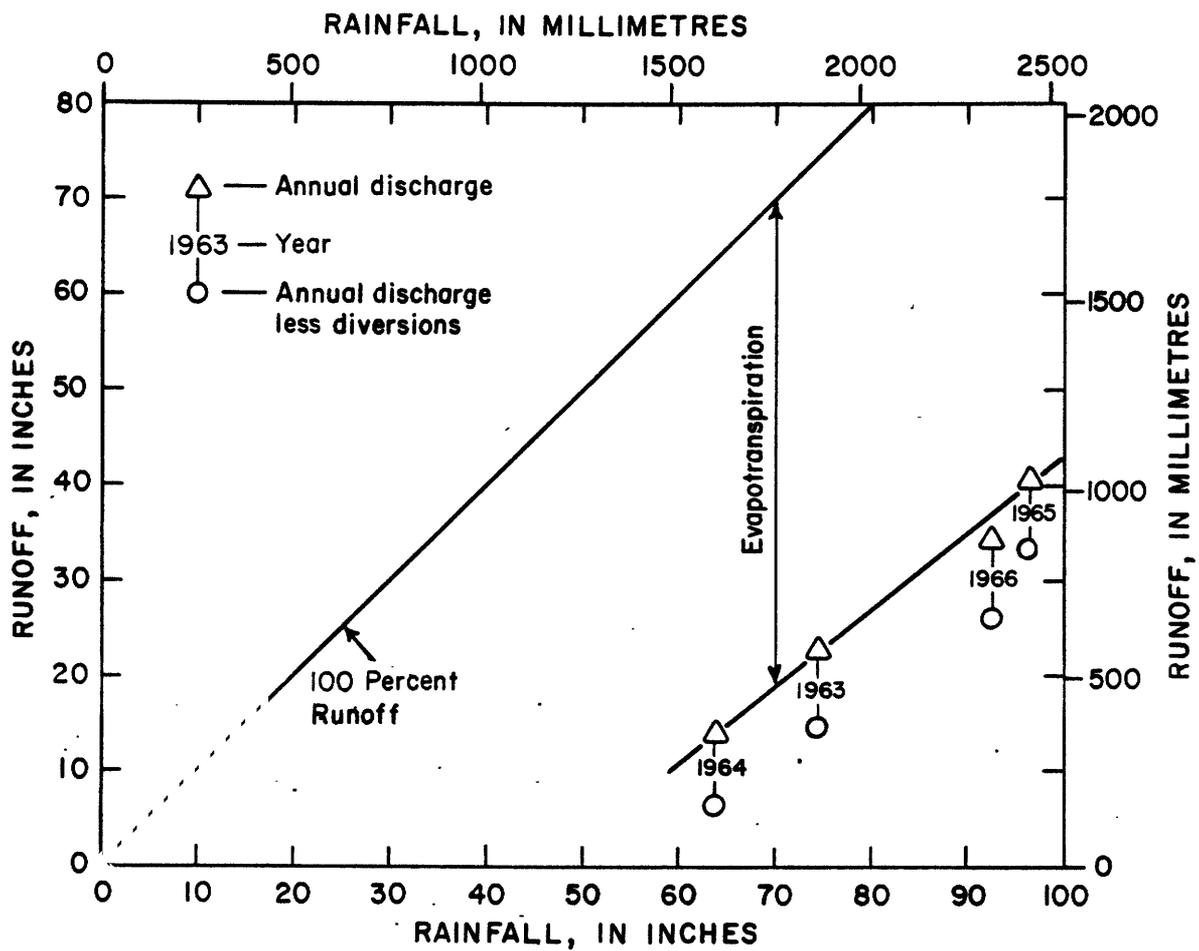


Figure 10.--Relationship of rainfall at Hato Tejas to discharge of Río de Bayamón at Bayamón (station 50 0480 00).

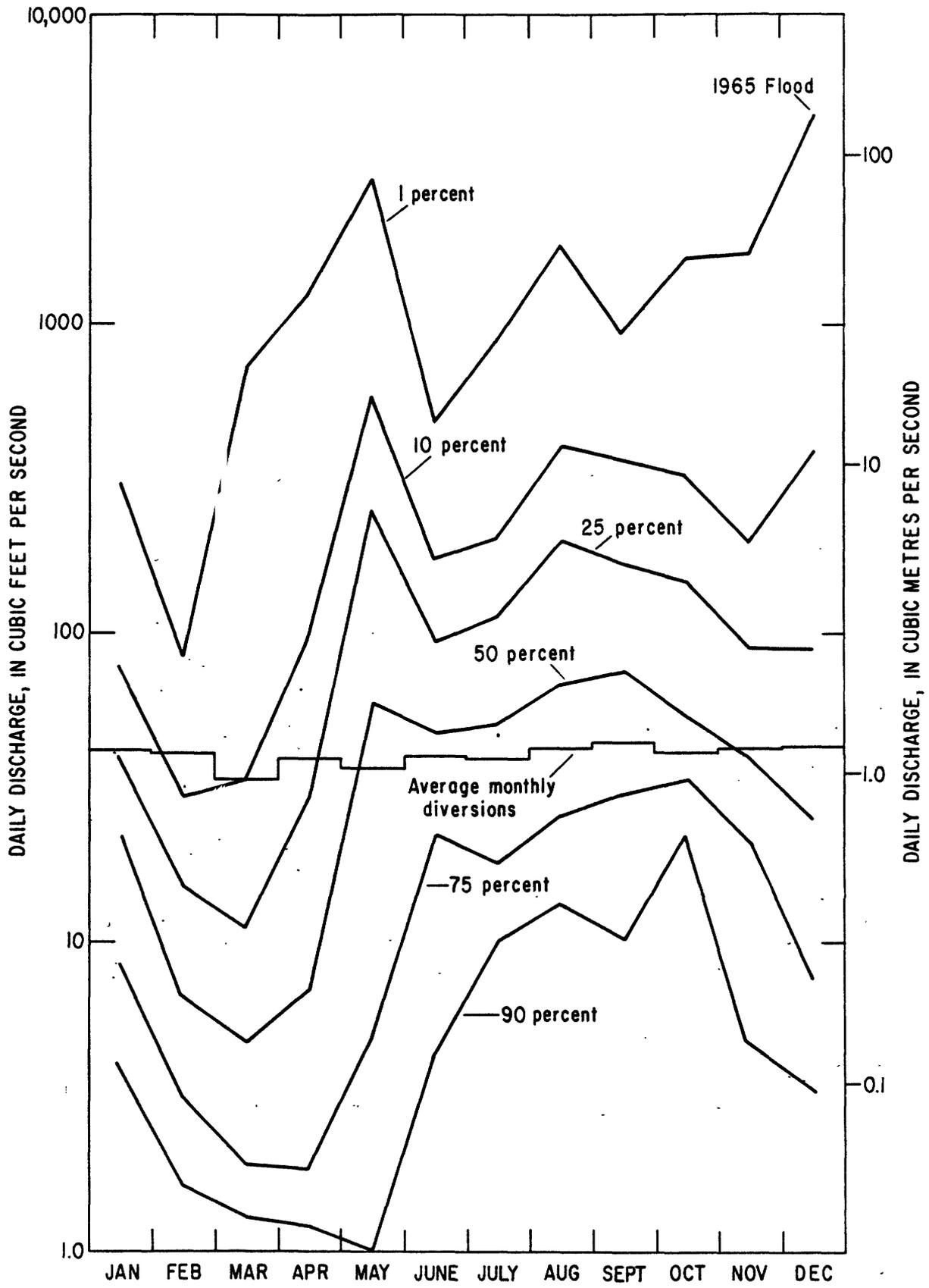


Figure 11.--Percentage of time that a certain mean-daily discharge was equaled or exceeded in any 1 month, January 1963 to December 1966, Rio de Bayamón at Bayamón (station 50 0480 00).

hand, follows a pattern similar to the monthly rainfall in the basin, as high, infrequent flows or floods are in direct response to intense rains.

The minimum flow in the 10-percent curve is in February, when storm runoff is least; whereas, the minimum in the 90-percent curve is in May, when the ground-water surface and base flow are lowest. The 10-percent curve shows highs in May and August, when rainfall and runoff are greatest; while, the 90-percent curve shows a high in October, when the ground-water surface is high and base flow is greatest.

Figure 12 shows the discharge, diversions, and sewage inflow of Río de Bayamón near Bayamón (station 50 0478 50) and Río de Bayamón at Bayamón (station 50 0480 00) for the first 4 months of 1966. The basin above both stations overlies volcanic rocks. The sites differ geologically only in the valley floor; for about 2 mi (3 km) above Río de Bayamón at Bayamón, the valley is filled with alluvium.

Base flow at the two stations, shown by the depletion curves, was high in early January; as the result of extremely heavy rainfall in the latter part of 1965. The first 3 months of 1966, however, were very dry with little rainfall, and the base flow reflects the depletion of ground water in storage in the volcanic rocks due to the lack of recharge. The steeper slope of the depletion curve of Río de Bayamón at Bayamón is attributed to losses of base flow to the alluvium in the riverbed.

Table 1 gives the average daily base flow per unit area for January, February and March 1966, at each station and also for that part of the basin between the stations. In January base flow was essentially the same at both stations. It can be concluded that the alluvium above the lower station was saturated and that ground-water discharge from the volcanic rock was at or near maximum. The following months show a steady decline in base flow at the upper station from a maximum of 1.28 to 0.73 (ft³/s)/mi² [14.0 to 8.0 (l/s)/km²]. Short-term data for drought periods indicated the ground-water contribution to streamflow from the volcanic rocks may be as small as 0.5 (ft³/s)/mi² [5 (l/s)/km²].

In February and March, the area between the two gaging stations showed a major decline in flow per unit area that is attributed to infiltration of streamflow into the alluvium. In both months, the apparent daily loss was about 0.3 (ft³/s)/mi² [3 (l/s)/km²] or about 6 x 10⁶ gal/day (0.26 m³/s) in 2 mi (3 km) of stream channel.

Downstream from the gaging station Río de Bayamón at Bayamón (station 50 0480 00) the river flows on alluvium across the outcrop of the San Sebastián Formation. Measurements, corrected for sewage inflow, made upstream and downstream of the outcrop of the San Sebastián Formation (area 1.3 mi² or 3.4 km²) on February 19, 1962, when base flow was high, showed a ground-water contribution of about 0.3 (ft³/s)/mi² [3 (l/s)/km²] to the stream. On March 4, 1963, at a low base flow a net loss of about 0.6 (ft³/s)/mi² [7 (l/s)/km²] was computed.

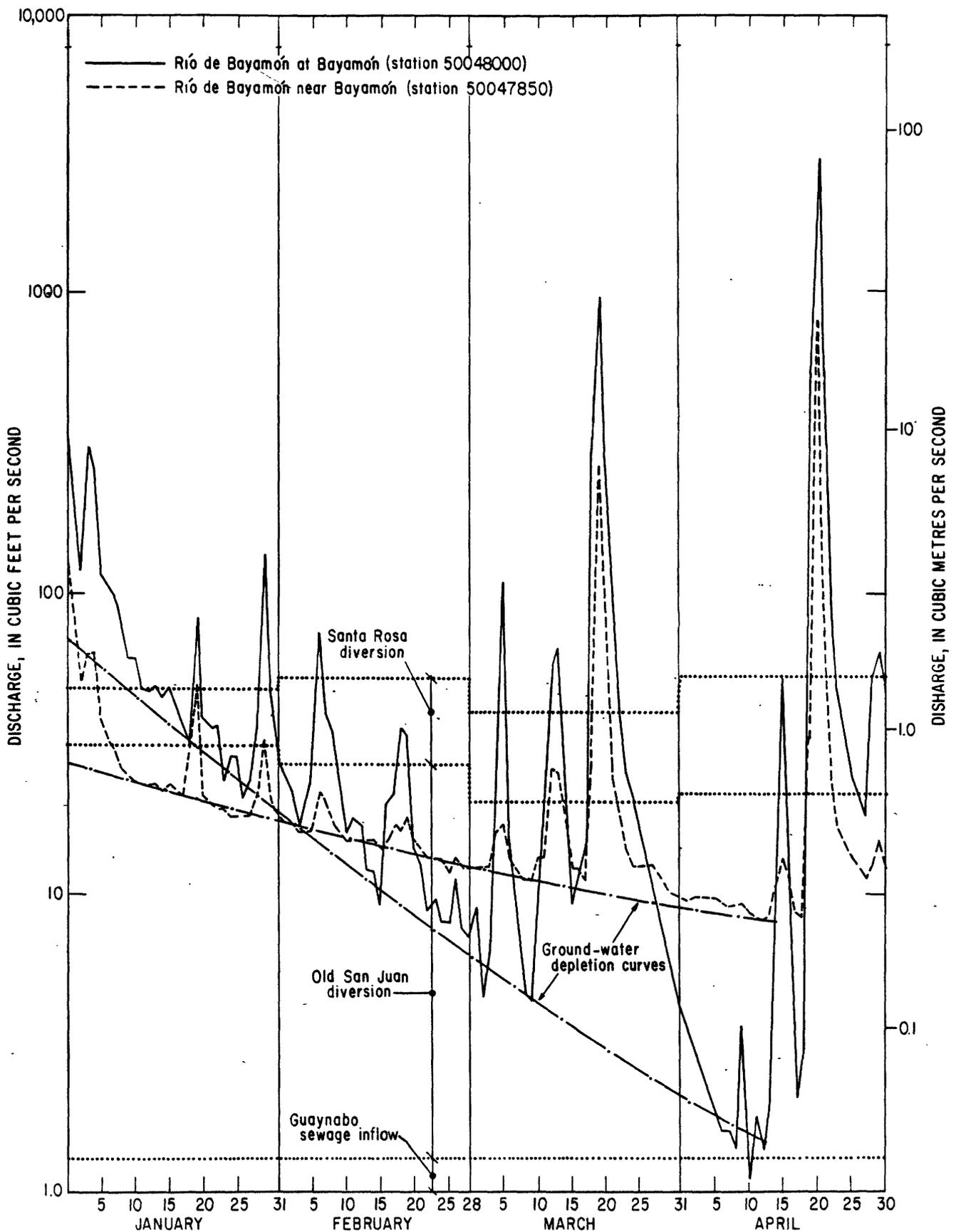


Figure 12.--Diversions of and sewage inflow to Río de Bayamón and discharge at Río de Bayamón near Bayamón (station 50 0478 50) and Río de Bayamón at Bayamón (station 50 0480 00), 1966.

Table 1.--Base flow of the Río de Bayamón, January-March 1966 (Discharge is in cubic feet per second)

Station	Drainage, square mile (km ²)	Date	Base flow, daily average	Diversions, daily average	Sewage, daily average	Total base flow	
						Daily average	(ft ³ /s)/mi ²
50 0478 50 (volcanic rock only)	41.8 (108)	Jan.	22	31.5	0	53.5	1.28
		Feb.	15.5	27.0	0	42.5	1.01
		Mar.	10.4	20.0	0	30.4	.73
50 0480 00 (alluvium over vol- canic rock)	71.9 (186)	Jan.	44	48	1	91	1.27
		Feb.	12	52	1	63	.88
		Mar.	4	40	1	43	.60
50 0480 00 minus 50 0478 50	30.1 (78.0)	Jan. Feb. Mar.				37.5 20.5 12.6	1.25 .68 .42

Gain or loss in flow of the Río de Bayamón, as it traverses the Aguada and Aymamón Limestones, is not known. In the basins west of the San Juan area, ground water from the limestone contributes from 21 to 50 percent of the runoff for seven major streams (Giusti and Bennett, in preparation). Because of the small areal extent of the limestones in the Bayamón area, the ground-water contribution probably is considerably less, and it may be that there is a net loss from the Río de Bayamón to the limestone.

The average precipitation (computed by the Thiessen method) for the Río de Bayamón basin in 1963-66 was 64 in (1,625 mm). Streamflow at Río de Bayamón at Bayamón station averages 28 in (710 mm) annually, including 8 in (205 mm) of diversions. Ground-water flow to the Río de Bayamón, but not accounting for losses to the alluvium upstream of the station, is largely from Cretaceous volcanic rocks and is estimated to be 15 in (380 mm) per year. The daily ground-water contribution to the river of 1.1 (ft³/s)/mi² [12 (l/s)/km²] was more than 50 percent of the total streamflow.

When ground-water levels are low, generally in the months of January through April, the alluvium and likely the Tertiary rock aquifers receive recharge from the river. In the upper 2 mi (3 km) of the alluviated valley, maximum stream loss is about 3 (10⁶ gal/day)/linear mi [0.08 (m³/s)/linear km] of channel. Downstream loss may be as great as 6 (10⁶ gal/day)/linear mi [0.16 (m³/s)/linear km] where the river crosses the outcrop of the limestones. On the coastal plain proper, the alluvium in and adjacent to the river channel is very fine to

clayey and the infiltration rate is probably much less than upstream. Hydrographs of wells and water quality of the Sabana Seca well field indicate some hydraulic connection between the limestone aquifer and the river.

If streamflow is available, an estimated 20×10^6 gal/day ($0.9 \text{ m}^3/\text{s}$) probably is recharged to the aquifers during the dry months. During the rest of the year, the aquifers either are in balance with the stream system or contribute water to the stream.

CHEMICAL QUALITY OF WATER

Ground Water

The chemical differences of ground water in the aquifers in the San Juan area are very slight. The predominant ground water is a calcium bicarbonate type. Some ground water is a sodium sulfate type; however, water of this type does not conform to any recognizable pattern of distribution.

Ground water generally becomes more mineralized from the mountain region toward the coast (fig. 13) where the occurrence of the more soluble limestone formations and seawater contribute to the mineralization of ground water.

A summary of analyses of water samples from the unconfined aquifer, principally the Aguada Limestone, shows the water to be alkaline (pH 7.7 to 8.3), moderately high in dissolved-solids concentration (293 to 4,550 mg/l) and very hard (110 to 1,100 mg/l) but otherwise of good quality (table 2). The aquifer is susceptible to salt-water intrusion and the uppermost formation, the Aymamón Limestone, contains brackish or seawater along much of the coastline.

Ground water from the Cibao and San Sebastián Formations in both the unconfined and confined parts of the aquifer is considerably less mineralized than the water from the limestone aquifer. A summary of analyses of water from these formations is given in table 3.

For comparison, the median concentrations of dissolved solids, hardness and bicarbonate for the Cibao and San Sebastián Formations are 363, 195, and 226 mg/l, respectively; whereas, the median concentrations for the limestone formations are 525, 295, and 300 mg/l, respectively.

Figures 14 and 15 show the generalized distribution of chloride concentration and hardness in the unconfined aquifers in the metropolitan area.

Table 2.--Summary of chemical analyses of water from wells in limestone of the unconfined aquifer (15 samples)

Parameter	Concentration mg/l			Median
	Minimum	Maximum	Average	
Silica.....	9.5	52	29	30
Calcium.....	23	190	93	77
Magnesium.....	5.4	160	28	18
Sodium.....	20	1,570	205	83
Potassium.....	.6	17	3.7	2.2
Bicarbonate.....	160	396	285	300
Sulfate.....	3.8	330	56	24
Chloride.....	22	2,400	330	120
Fluoride.....	.0	.9	.2	.15
Nitrate.....	.0	12	2.6	.9
Dissolved solids ..	293	4,550	867	525
Hardness.....	110	1,100	344	295
Conductance (umhos)	517	7,680	1,500	920
pH.....	7.7	8.3	--	7.8
Temperature °C ...	25	27.8	26.1	26

Table 3.--Summary of chemical analyses of water from wells in sand of the confined aquifer (17 samples)

Parameter	Concentration, mg/l			Median
	Minimum	Maximum	Average	
Silica.....	9.6	56	38	43
Calcium.....	14	92	57	58
Magnesium.....	2.3	20	12.9	11
Sodium.....	10	120	57.5	46
Potassium.....	1.2	46	5.8	3
Bicarbonate.....	120	364	230	226
Sulfate.....	6	170	47	23
Chloride.....	17	190	57	34
Fluoride.....	.0	.4	.14	.1
Nitrate.....	.0	85	7.5	.6
Dissolved solids ...	253	619	400	363
Hardness.....	45	290	195	195
Conductance (umhos) .	361	1,070	645	625
pH.....	7.3	8.5	--	8.0
Temperature °C	24.5	27.5	25.7	25.5

POSSIBILITIES FOR FURTHER INVESTIGATION

Deep Test Well

In metropolitan San Juan, a deep test well could be drilled to explore the geologic and hydrologic environment below 300 ft (90 m). In the present state of knowledge, the geologic composition and structure beneath San Juan is largely unknown. The specific objectives of a deep-well program would be threefold: 1) to test the sand and marl aquifer for artesian water at depth; 2) to determine the aquifer's hydraulic characteristics and extent of salt-water intrusion; and 3) to determine the feasibility of recharging aquifers through wells or subsurface storage of liquid wastes through wells.

Artificial Recharge

Further investigation could reveal if artificial recharge may have practical application in San Juan. Surplus runoff from upland streams might be used to recharge aquifers through wells or pits. The additional head might tend to move the salt-water front seaward, thereby safeguarding existing aquifers or possibly reclaiming a contaminated aquifer. The sand and marl aquifer possibly could be recharged through injection wells to create a reservoir to be tapped during drought.

Specific sites that might be suitable for recharge include: 1) the foothills of Montes de Hatillo on the San Sebastián Formation intake area; 2) the Sabana Seca Naval Station between the mogotes of the Aguada-Aymamón Limestone and in conjunction with this, the level of Caño El Hato could be raised, thereby creating a hydraulic barrier to seawater encroachment; and 3) a recharge pit in the intermogote valley, bottomed by the Cibao Formation and surrounded by Aguada Limestone hills, at Ft. Buchanan. The pit could recharge and freshen aquifers presently used in Las Palmas industrial area to the north. In addition, recharge wells installed north of the industrial area could act as a hydraulic barrier to seawater intrusion.

A collapsible dam or a tidal gate on the Río de Bayamón floodway, to prevent salt water from moving up the channel from the sea, has been considered by planners. Consideration might be given to an investigation of the effect on the aquifer with and without a control.

Effect of Urbanization on Recharge Areas

If runoff due to urbanization increases, there should be concomitant decreases in ground-water recharge to the aquifers. Investigation could determine the effects of urbanization on the ground-water reservoir and the extent of seawater intrusion. Some recharge areas have been cemented over or otherwise destroyed by construction.

North Coast Artesian Aquifer

Evidence is accumulating that an extensive artesian aquifer exists throughout the north coast. The confined sand aquifer represents this zone in the San Juan area. Artesian water has been found at Manatí, 1,200 ft (370 m) below sea level; near Barceloneta, 900 ft (270 m) below sea level; and at Arecibo, 2,300 ft (700 m) below sea level, from an electric log of an oil-test well. Yields are as much as 2,000 gal/min (130 l/s). Though the aquifer varies from relatively pure limestone to sand and marl, a fairly uniform confining layer is provided by the Cibao clay. Further investigation is needed to determine the potential of this aquifer throughout the north coast, particularly where the upper aquifers are salty or where large quantities of water are desired.

Modeling

Hydrologic conditions in the San Juan area could be simulated by an analog or digital model. Such a model probably would facilitate additional studies of the area and would be a valuable tool in evaluating the effects of existing or proposed water-related developments on the system.

RESUME OF PRINCIPAL FINDINGS

1. The principal aquifers in the San Juan metropolitan area are the unconfined limestone aquifer--composed of the upper part of the Cibao Formation, the Aguada and the Aymamón Limestones, and the artesian sand aquifer--composed of the lower part of the Cibao and San Sebastián Formations. Clay layers in the Cibao Formation and probably clayey alluvium act as confining beds of the artesian aquifer.

2. The yield of the unconfined limestone aquifer is much greater than that of the artesian sand aquifer. For example, average yields respectively are 510 gal/min (32 l/s) versus 240 gal/min (15 l/s) and specific capacity 41 (gal/min)/ft [8.5 (l/s)/m] versus 3 (gal/min)/ft [0.6 (l/s)/m]. The transmissivity of the unconfined limestone aquifer is as much as 135,000 ft²/day (12,500 m²/day), and that of the artesian sand aquifer is usually less than 2,500 ft²/day (230 m²/day).

The unconfined aquifer is susceptible to seawater intrusion; whereas, the artesian aquifer has not encountered this problem.

3. A hydrologic analysis of the Río de Bayamón basin indicates that for 1963-66 the

average annual precipitation was about 64 in (1,630 mm), at Hato Tejas. Of this amount, basin runoff amounted to 28 in (710 mm). Approximately 15 in (380 mm) represents ground-water flow from Cretaceous volcanic rocks to the Río de Bayamón. This is essentially the base flow of the stream. In the dry season, practically all this base flow is diverted for supply. The annual evapotranspiration from the basin is about 36 in (915 mm).

4. Areas blocked out as being unfavorable for ground-water development include the unconfined limestone aquifer north of lat 18° 26' N, which yields brackish water, and unconfined volcanic rocks in the uplands south of San Juan, which are low yield.

5. Ground-water pumpage in past decades has changed from 5×10^6 gal/day (220 l/s) in 1945 to 3×10^6 gal/day (0.13 l/s) in 1970.

6. Locations for drilling high-yield wells in the unconfined limestone aquifer are most promising between Campanilla and Sabana Seca and, in San Juan bordering the southern shores of San José Lagoon. Though yields in the limestone improve to the north, so does the chance for salt-water intrusion. Moderate yields can be developed from the confined sand aquifer beneath areas where the limestone aquifer is brackish.

7. The chemical characteristics of ground water in the aquifers are similar. Except for some isolated occurrences, water is predominantly of the calcium bicarbonate type. The dissolved-solids concentration, in the ground water, shows a progressive increase from the Cretaceous volcanic rocks to the Tertiary sandstones and limestones. Water in the limestone is the most highly mineralized.

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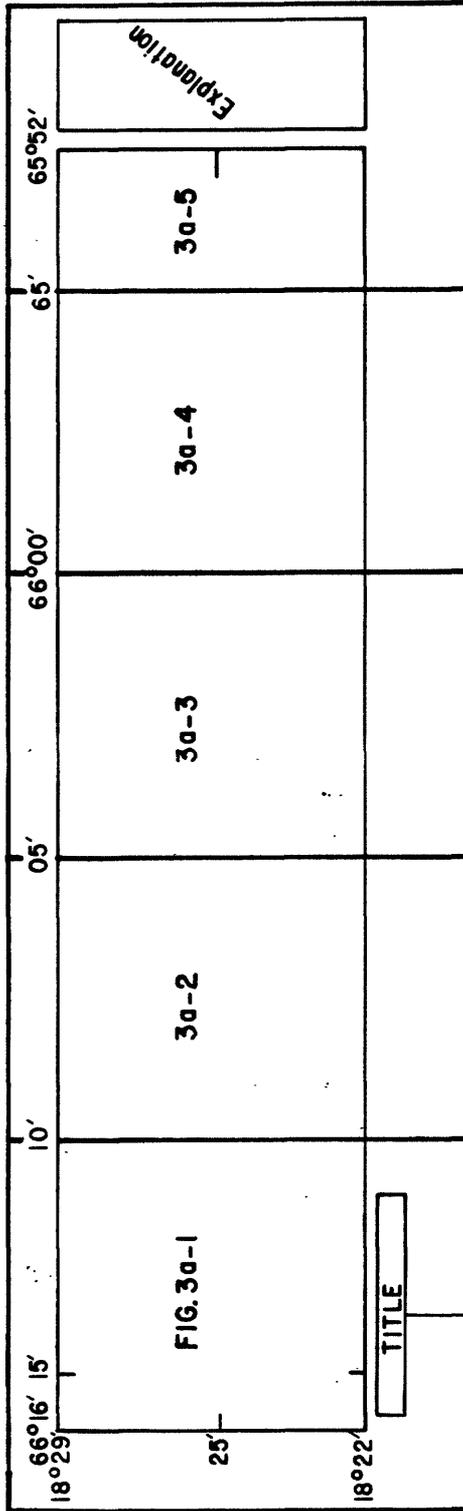
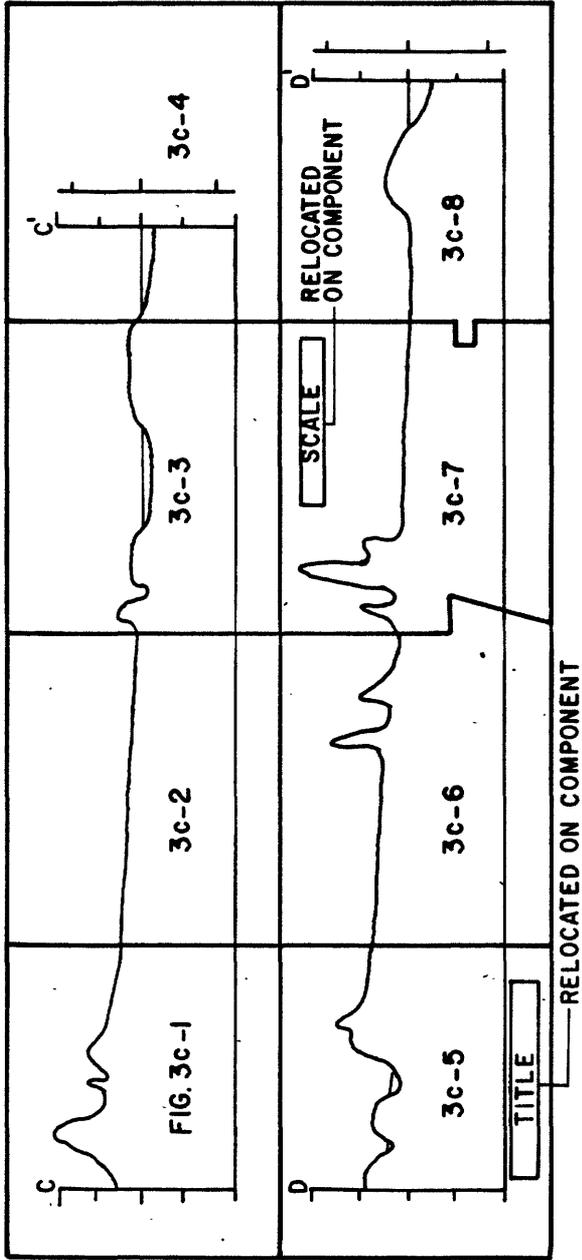
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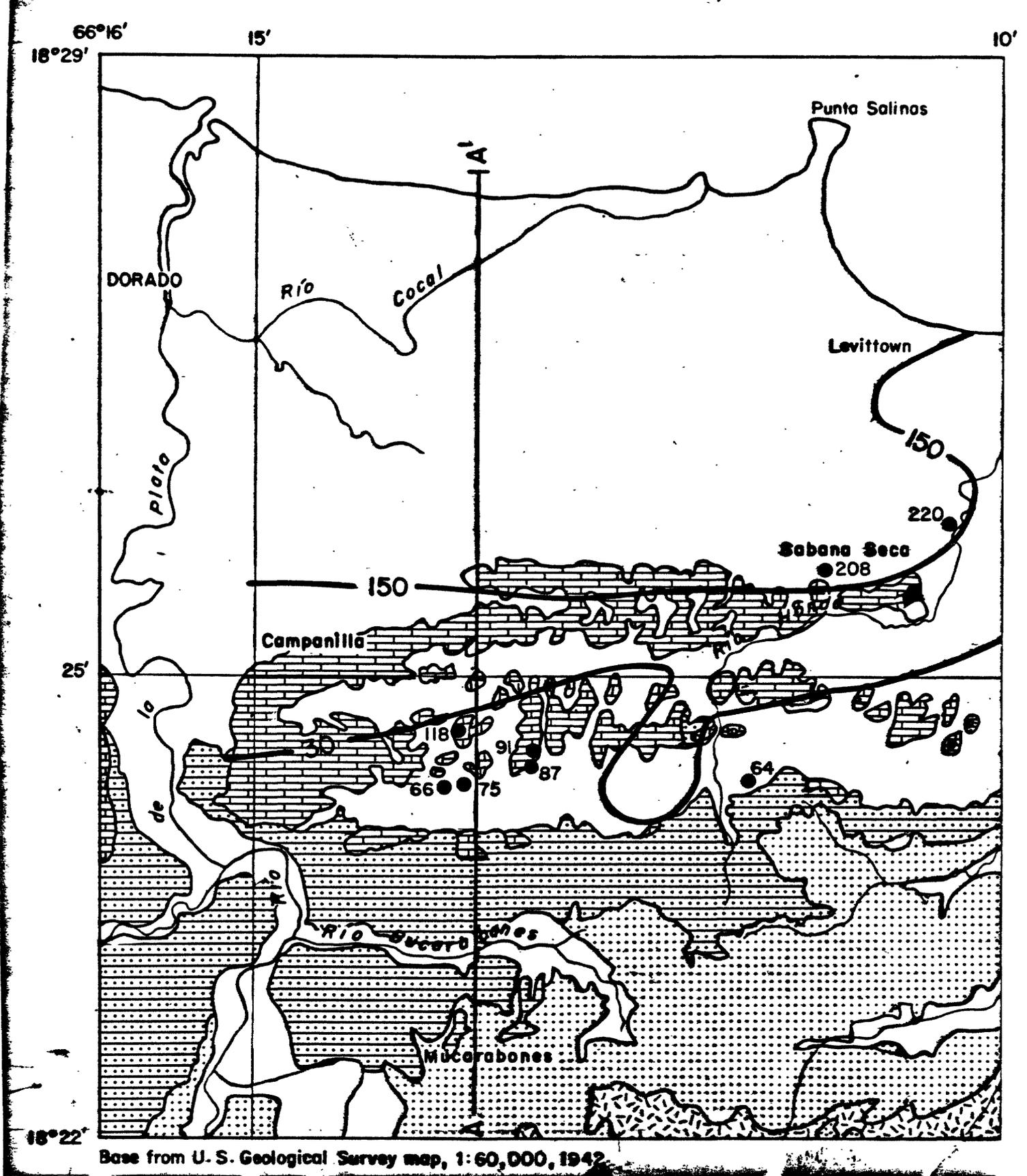
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(FIGURES 3c AND 3a COMPOSE THIS 18"x24" PLATE)

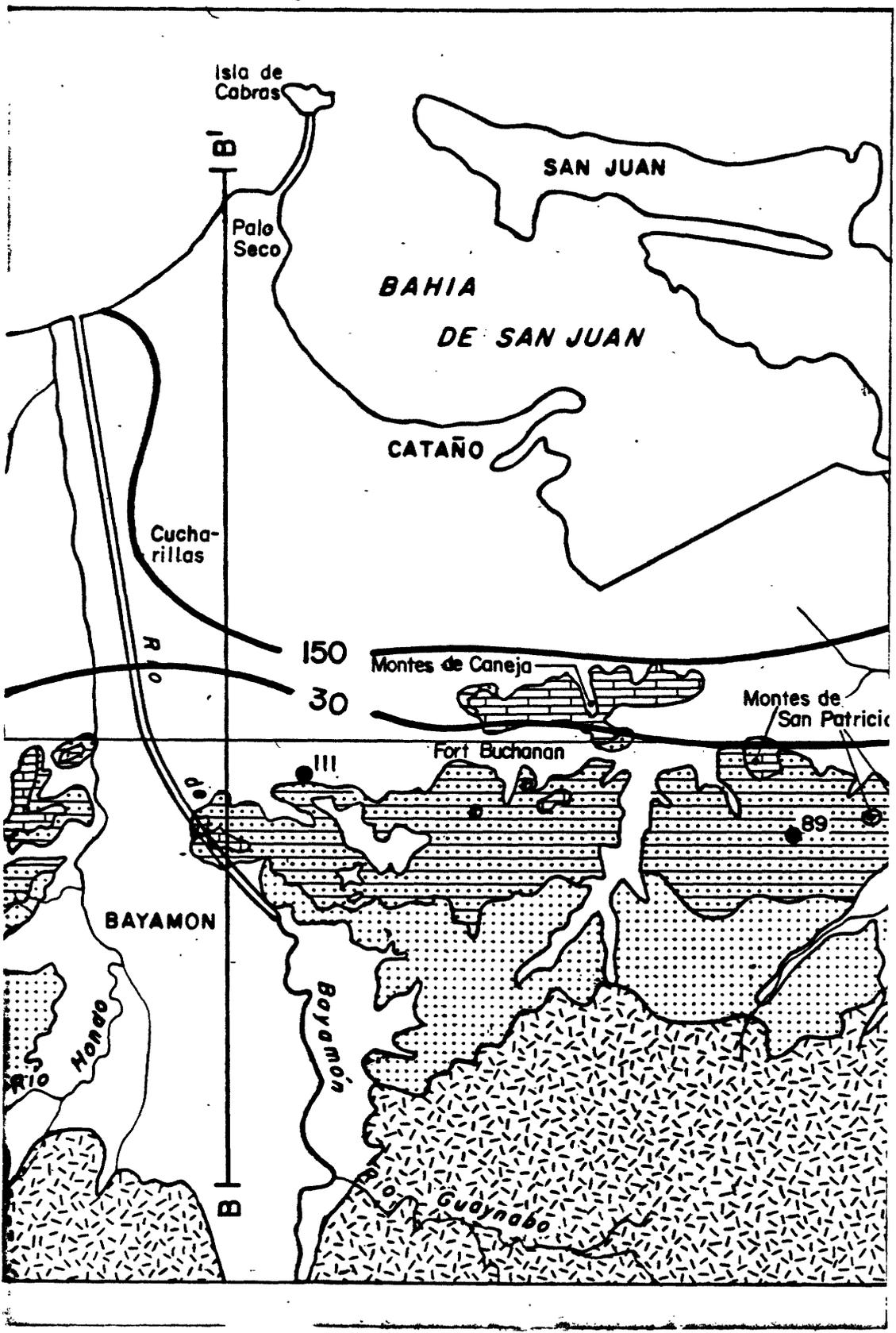
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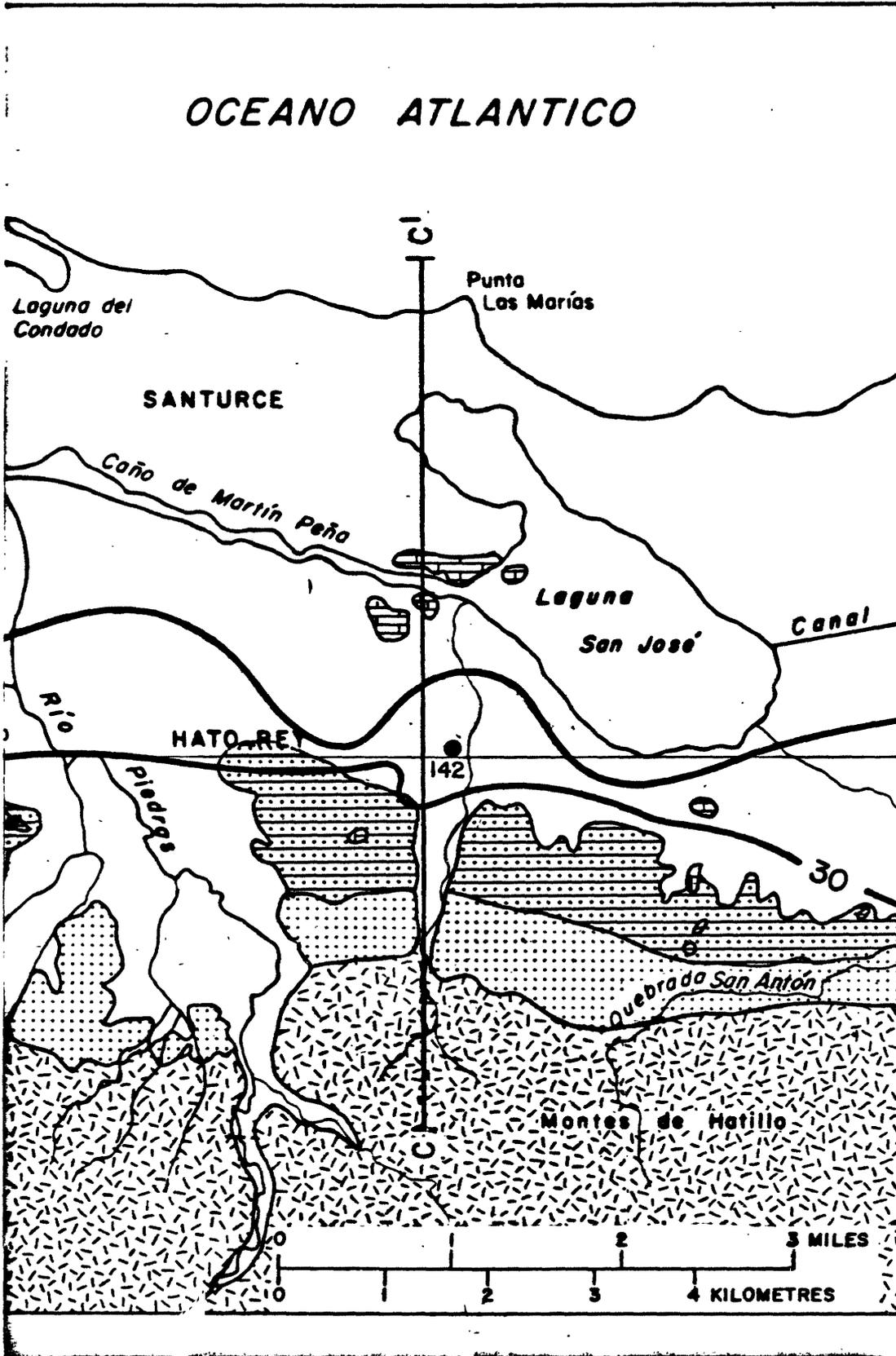
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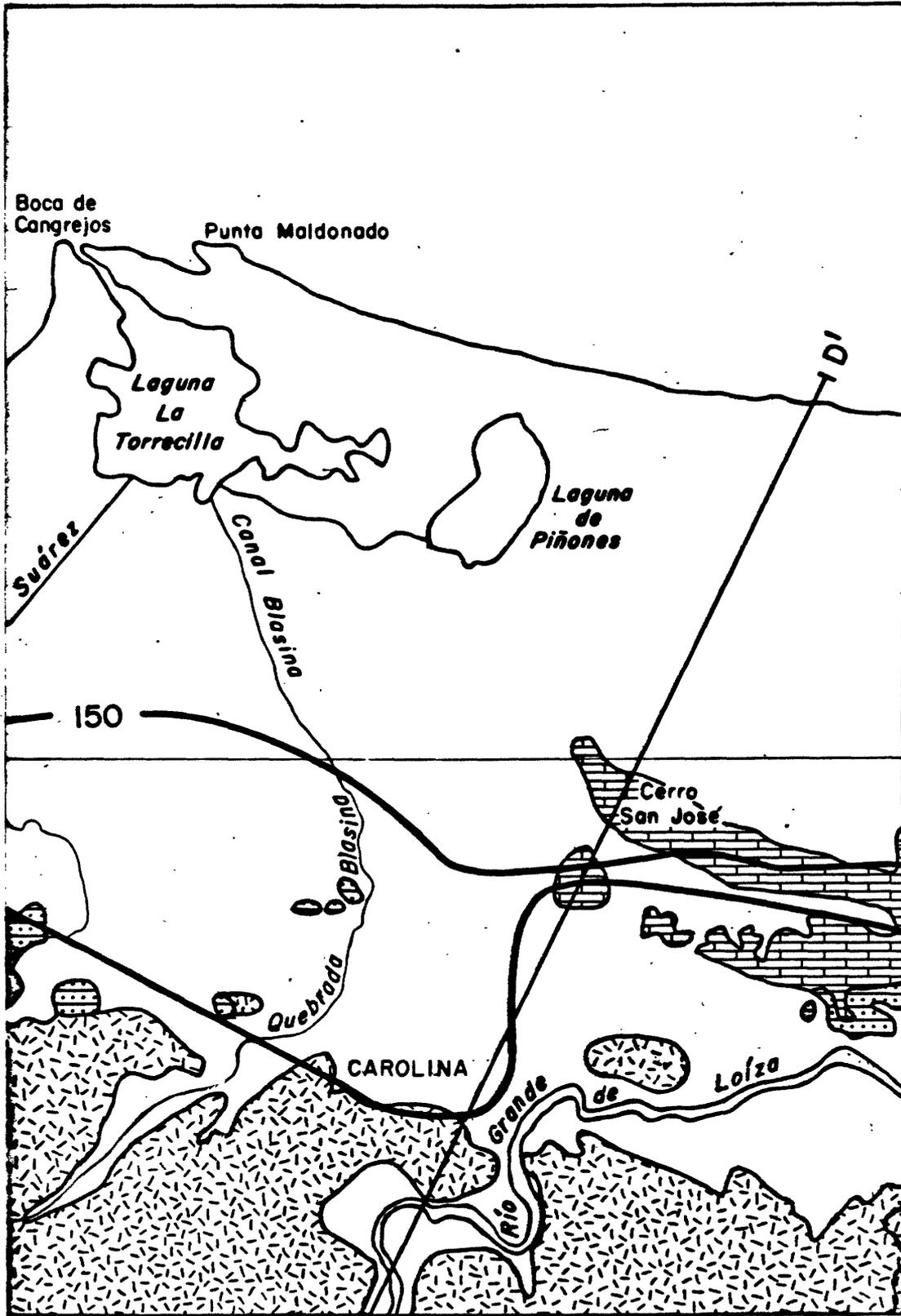


3a-1

FIGURE 3a -- HYDROGEOLOGIC MAP SHOWING GENERAL TRANSMISSIVITY OF AQUIFERS.



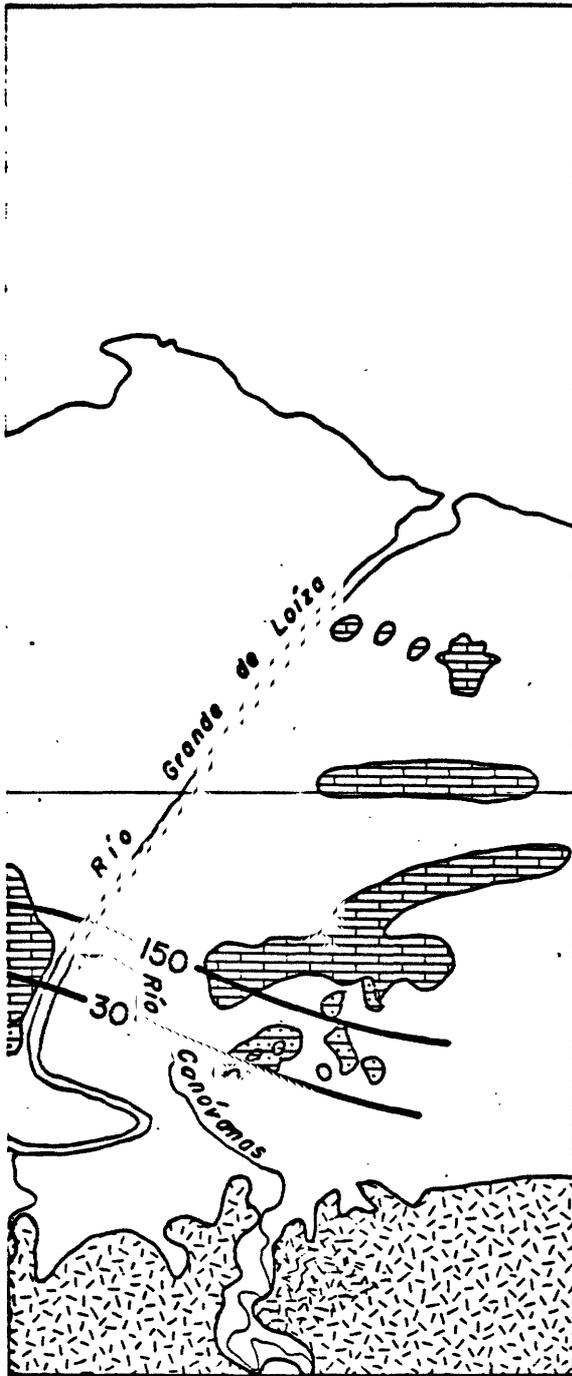




Geology after Kays (1959)

39

65°52'



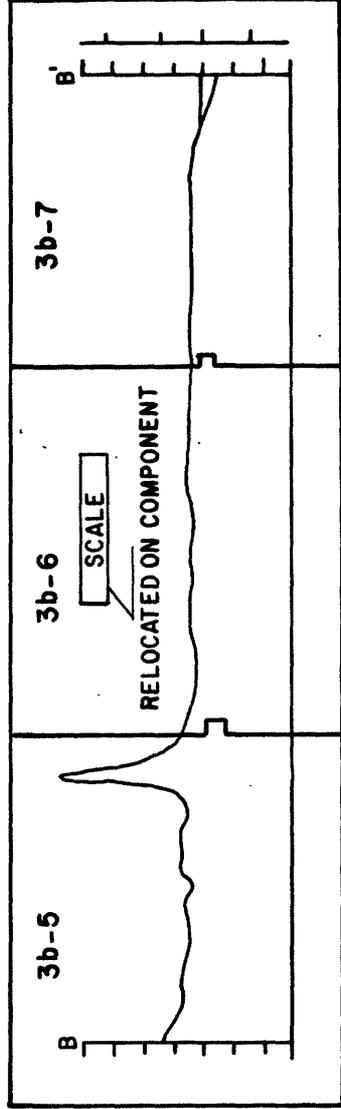
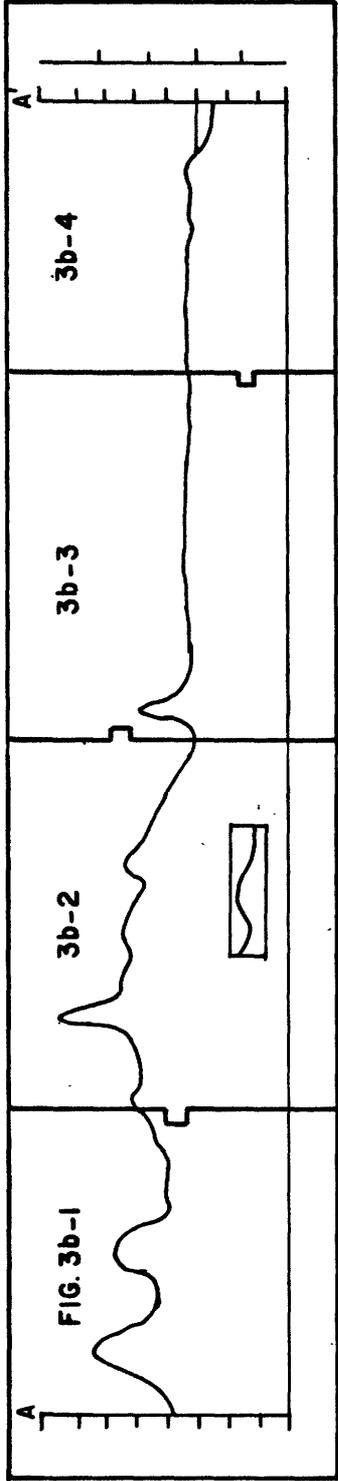
Monroe and Pease (1962).

EXPLANATION

Miocene to Holocene		TERTIARY TO QUATERNARY
	<p>Surficial deposits Clay, silt, sand, gravel, and peat in river terraces, blanket sand deposits, beaches, dunes, and marshes. Not important as an aquifer.</p>	
Miocene		TERTIARY
	<p>Aymamon and Aguada Limestones Aymamon is dense crystalline limestone. Yields as much as 2000 gal/min (126 l/s) to wells but contains mostly salt water. Aguada is thick-bedded calcarenite and dense limestone. Average yield to wells, 540 gal/min (34 l/s). Susceptible to sea-water intrusion.</p>	
Oligocene and Miocene		TERTIARY
	<p>Cibao Formation Interbedded clay, marl, sand, and limestone. Grades into San Sebastián Formation. Clay is confining layer.</p>	
Oligocene		TERTIARY
	<p>San Sebastián Formation Clay, sand, and gravel beds. Within lower part of the Cibao Formation is an artesian aquifer yielding as much as 500 gal/min (32 l/s) to wells. Includes overlying Muca-rabones Sand in western part of the area.</p>	
		CRETACEOUS AND TERTIARY
	<p>Volcanic rocks Volcanic siltstone, sandstone, and lava. Includes some limestone and intrusives. Average yield to wells, 50 gal/min (3 l/s). Water-bearing zone in fractured and weathered rock.</p>	
		
	<p>Contact</p>	
		
	<p>30</p>	
	<p>Line of equal transmissivity. Interval 120 feet squared per day (11 metres squared per day)</p>	
		
	<p>Geologic section</p>	
		
	<p>37</p>	
	<p>Well and number</p>	

3a-5

40

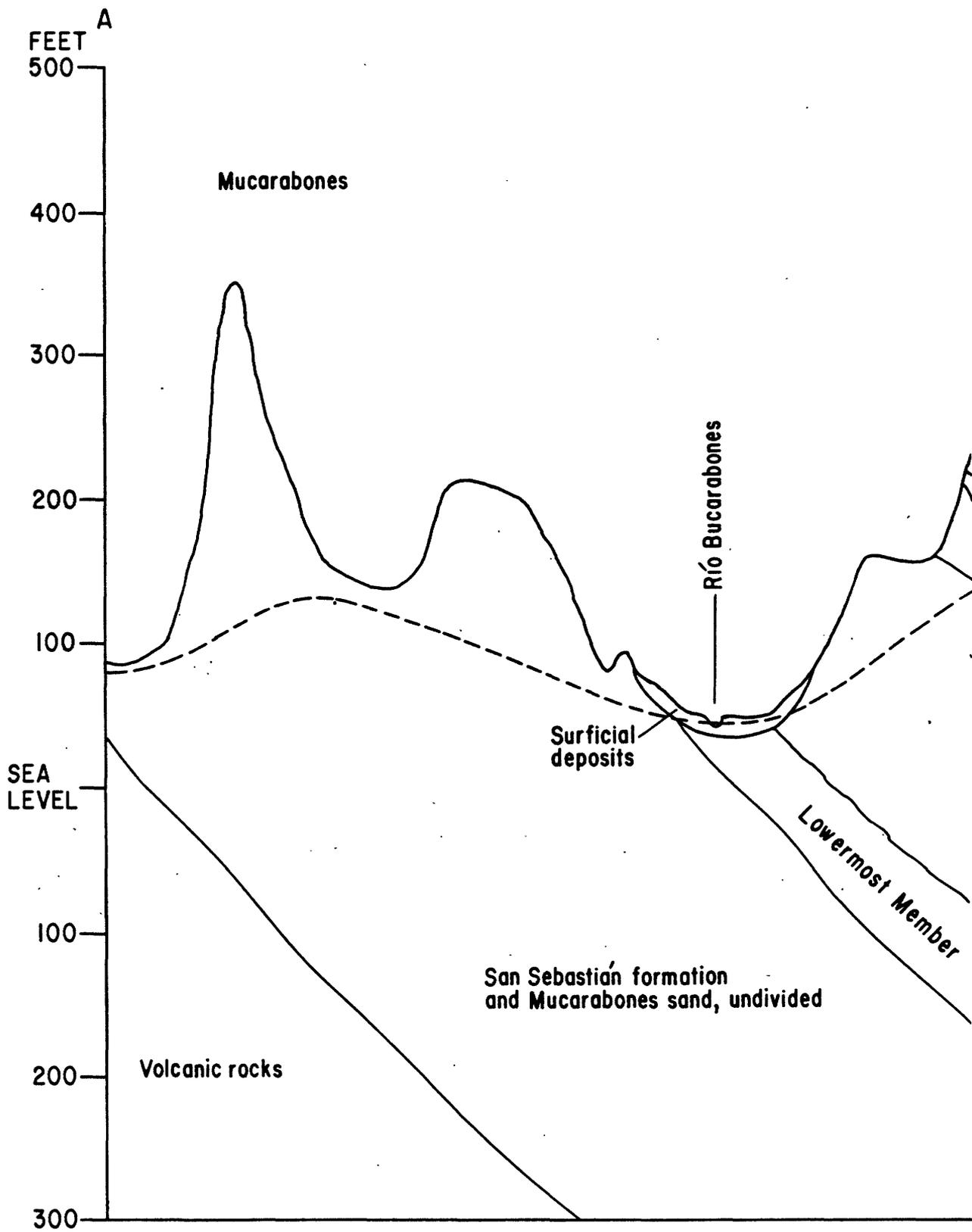


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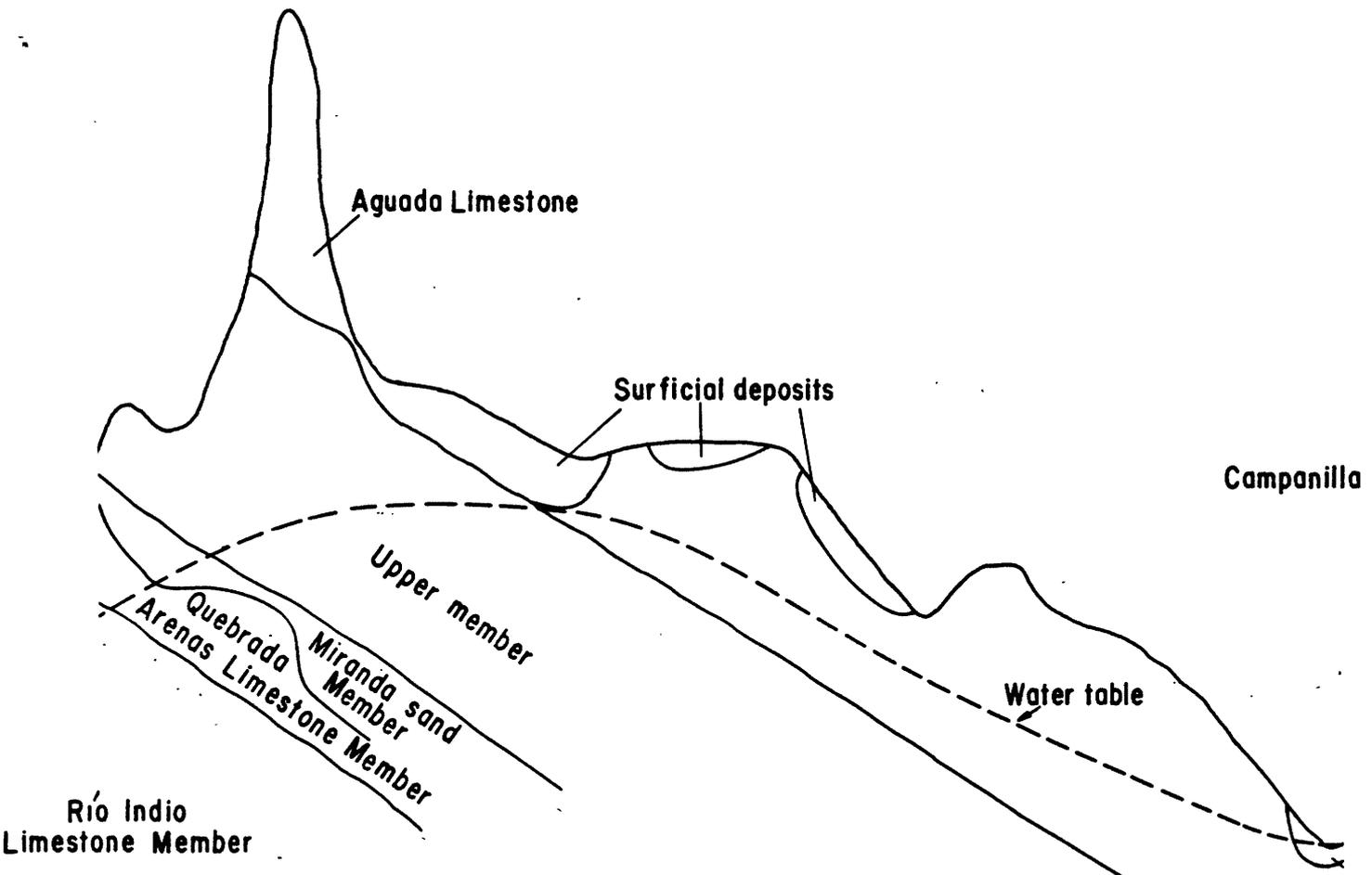
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(SECTIONS A-A' AND B-B' COMPOSE THIS FIG. 3b IN A 18"x24" PLATE)

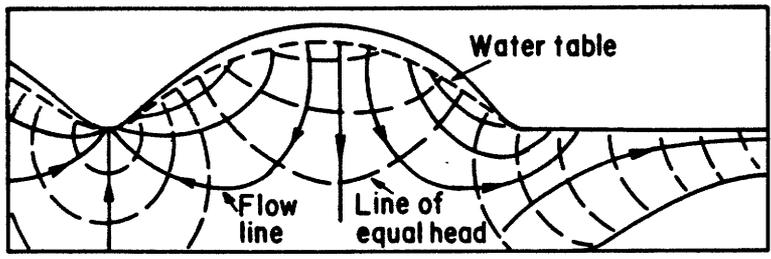


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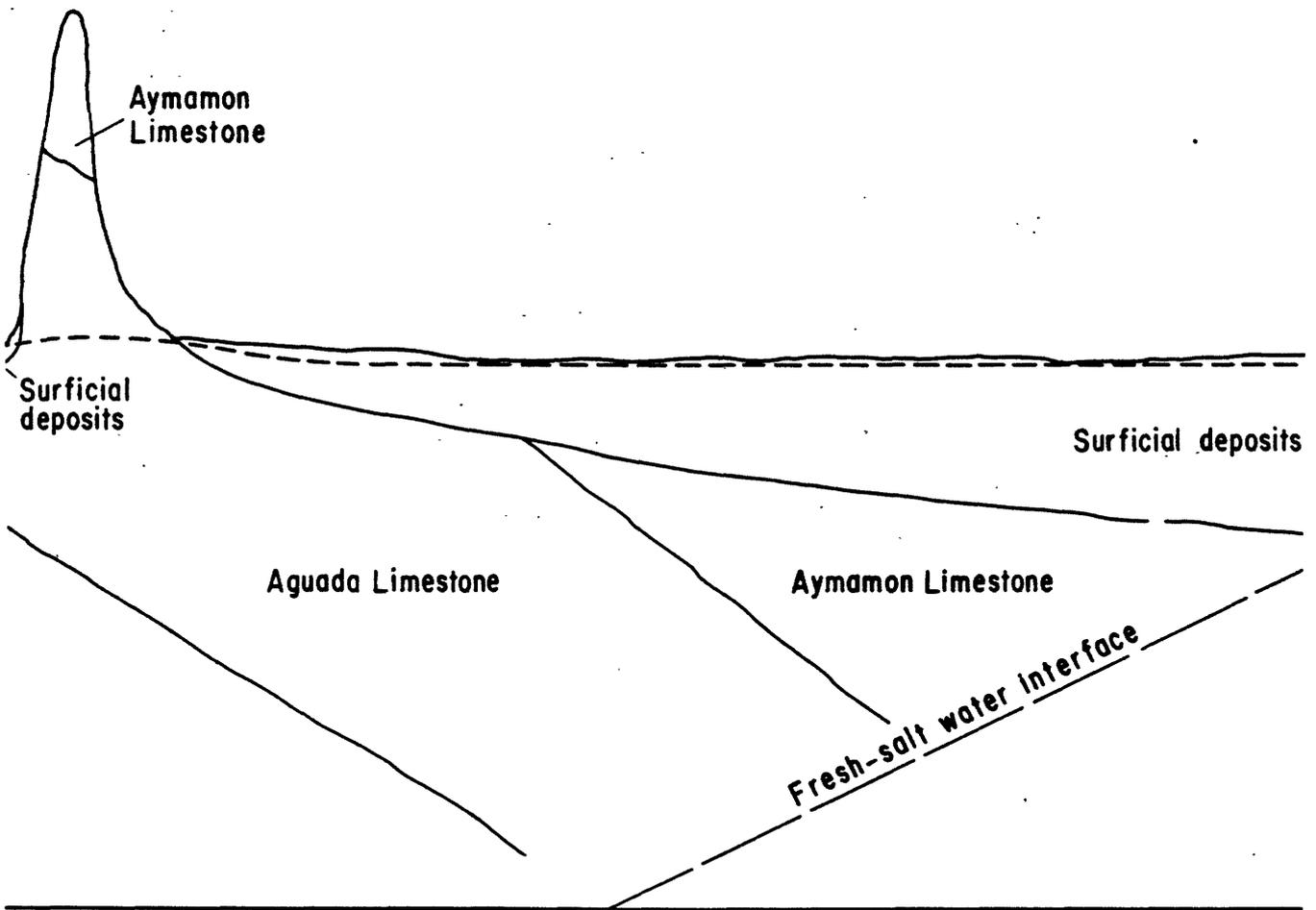
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Cibao formation



Sabana Seca

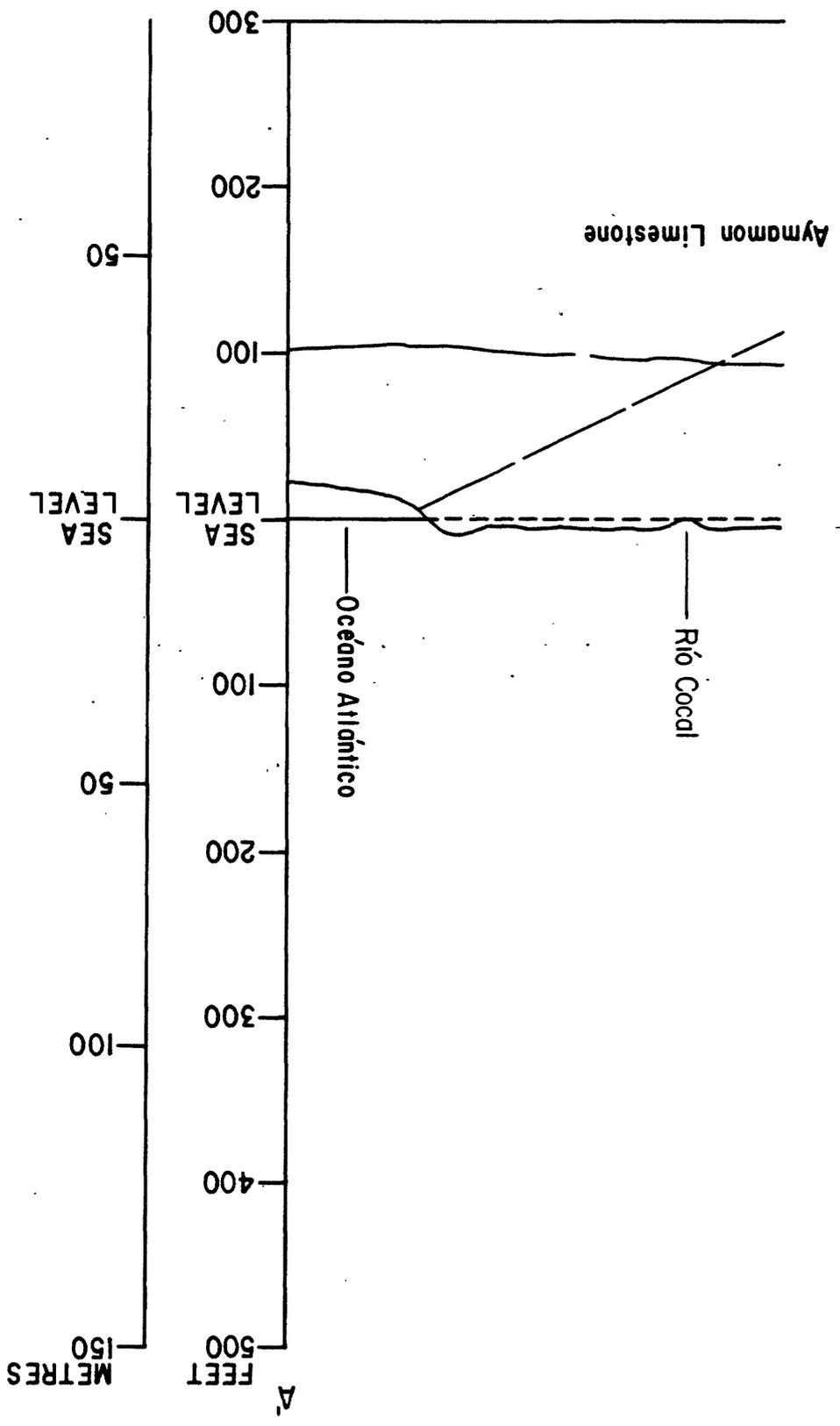


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3b-4



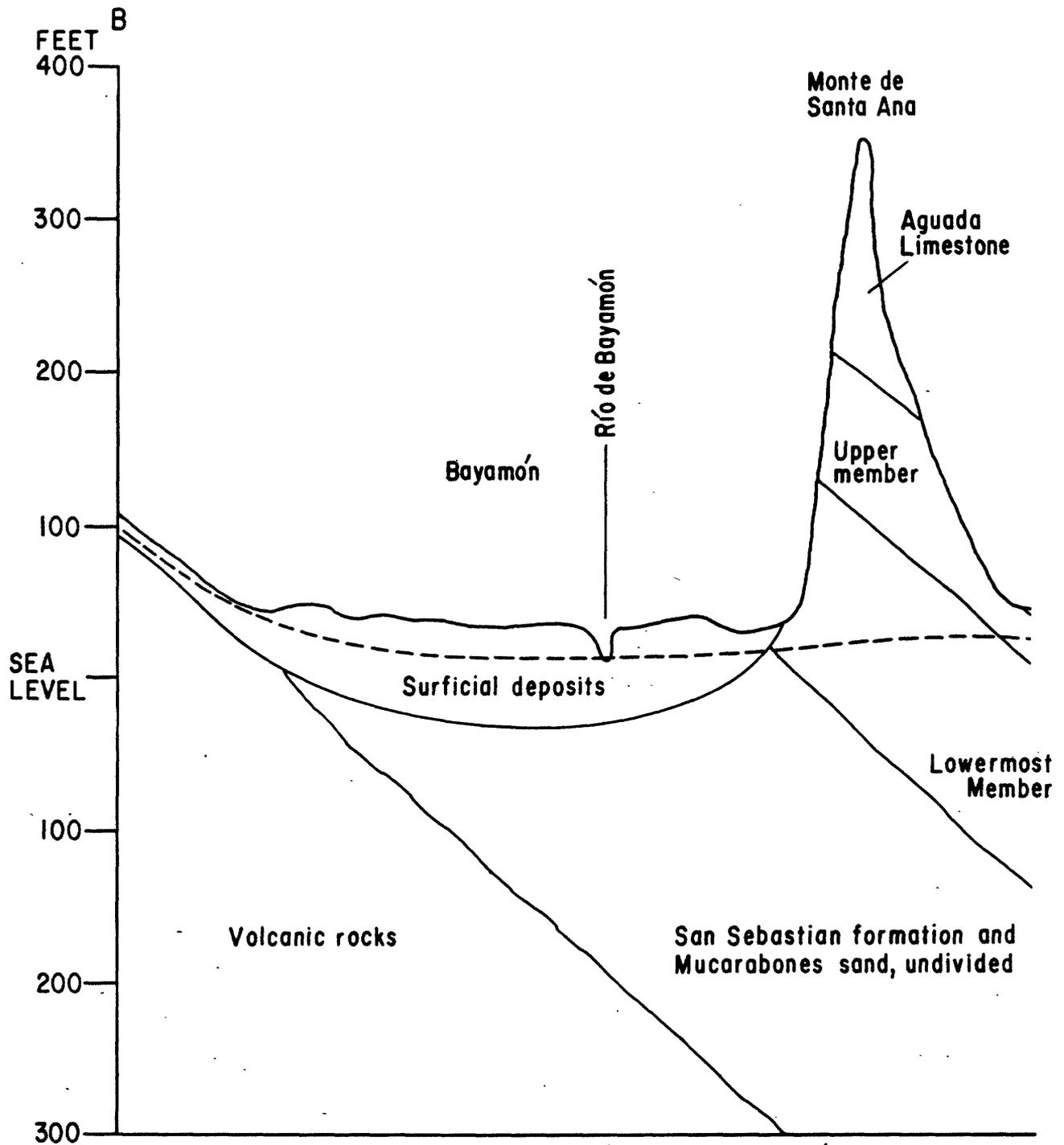
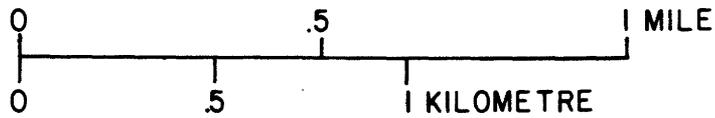


FIGURE 3b -- CROSS-SECTIONS

SEE LOCATION ON FIG. 3a

3b - 5

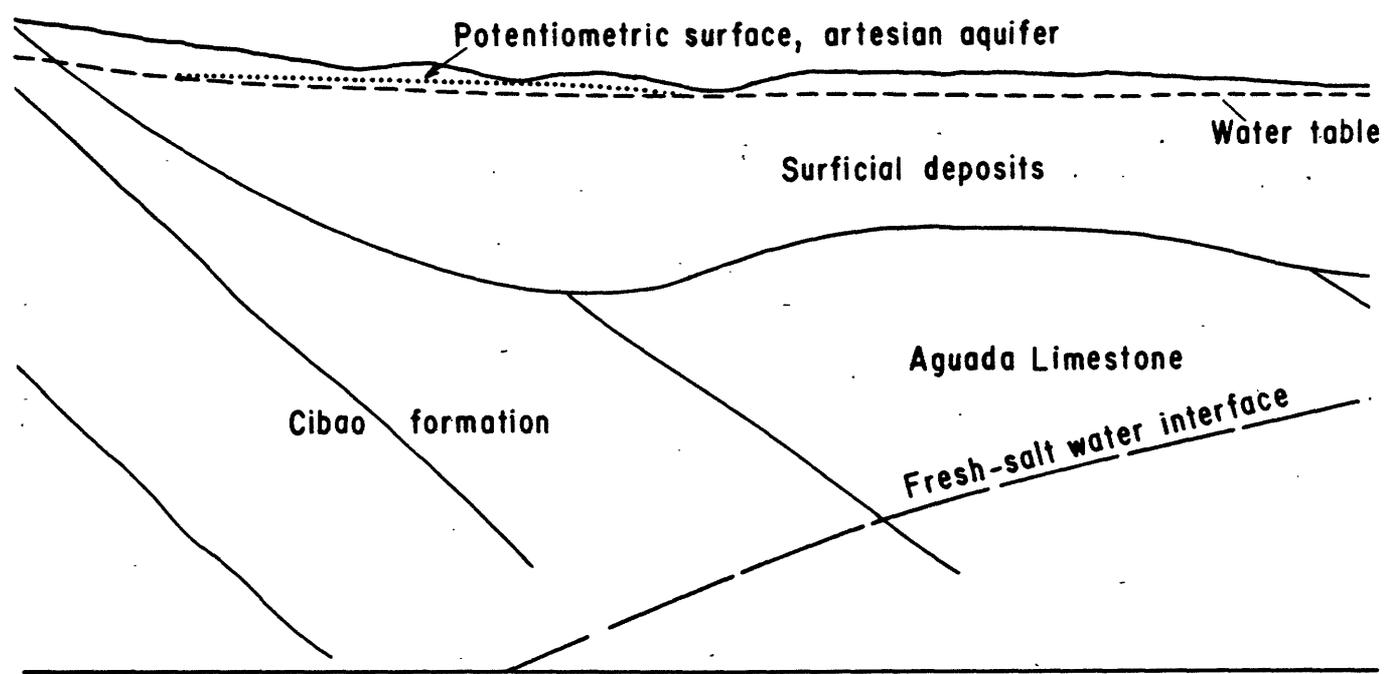
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HORIZONTAL SCALE FOR BOTH SECTIONS

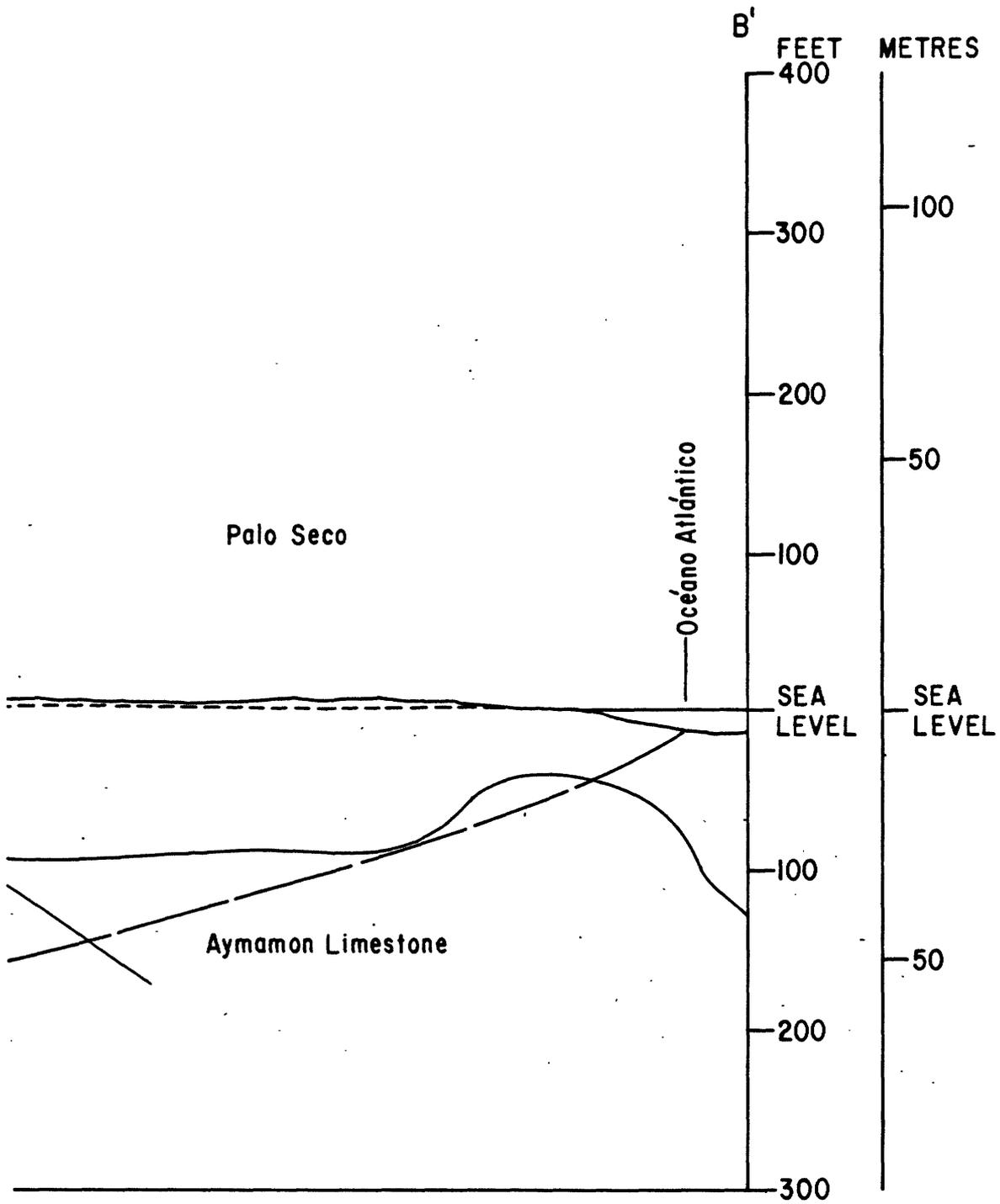
See fig 3a for definitions of the geologic formations

Cucharillas



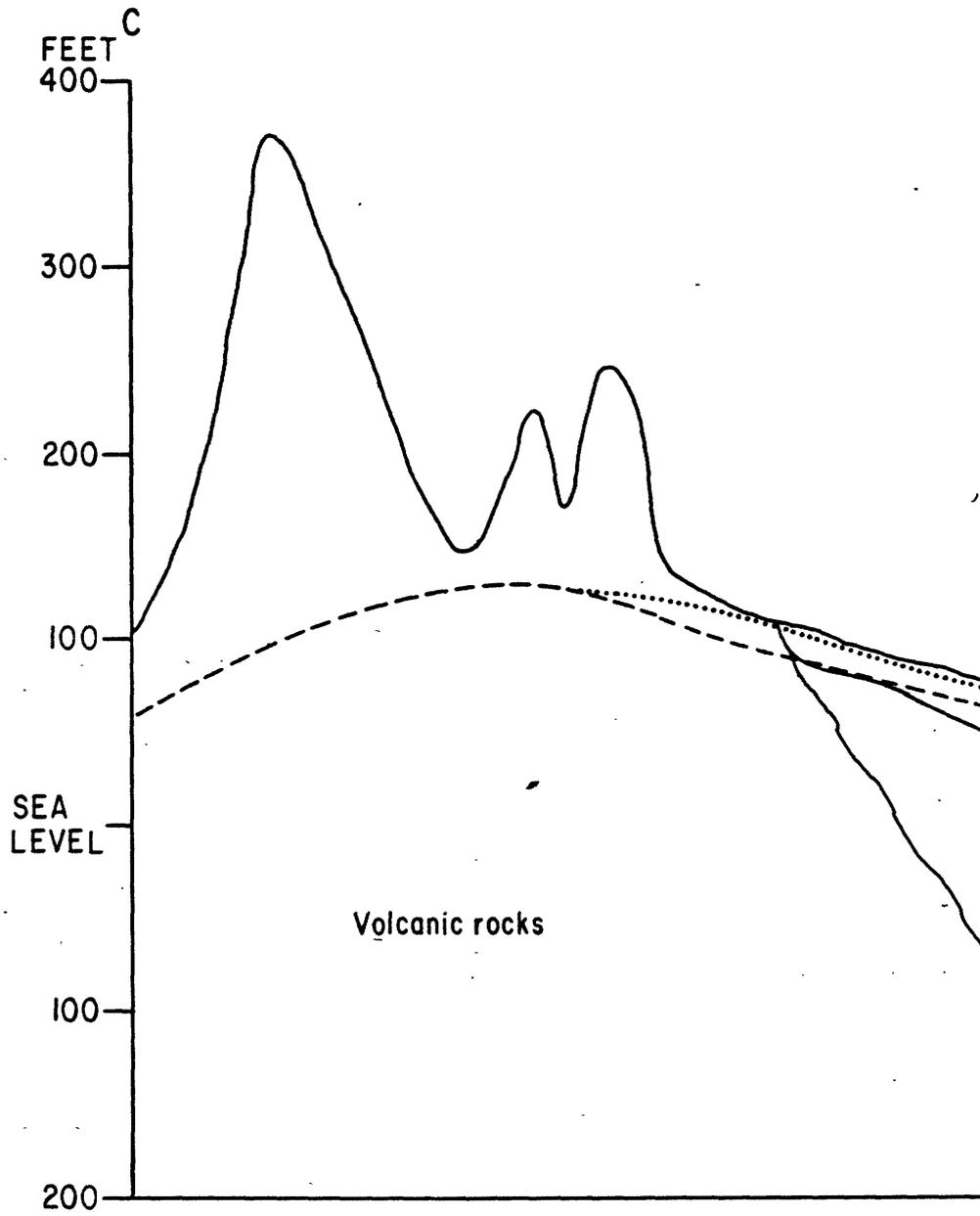
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47



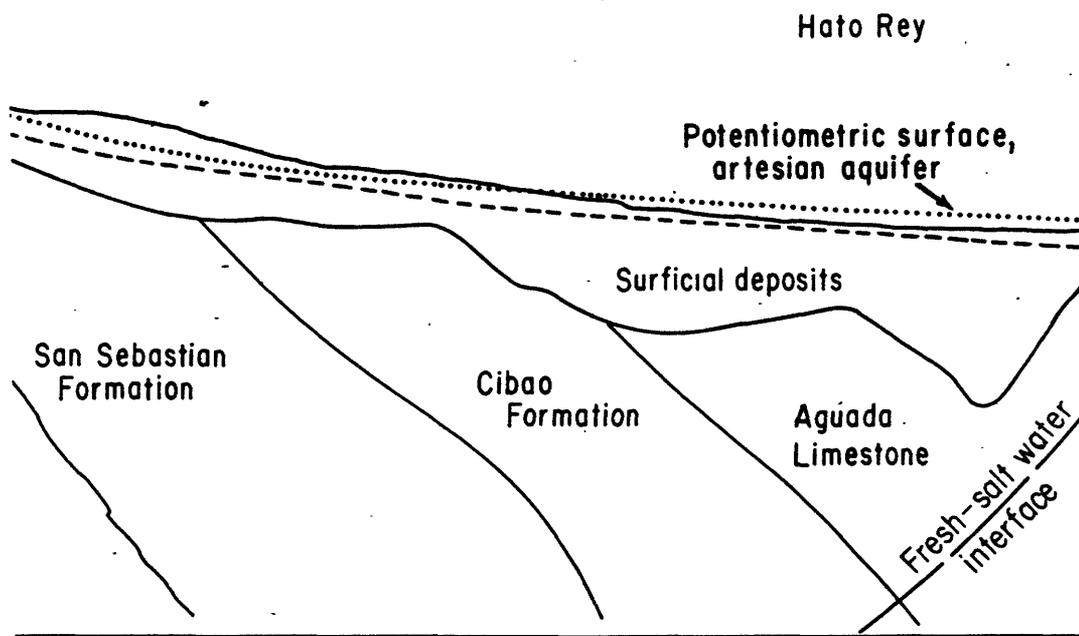
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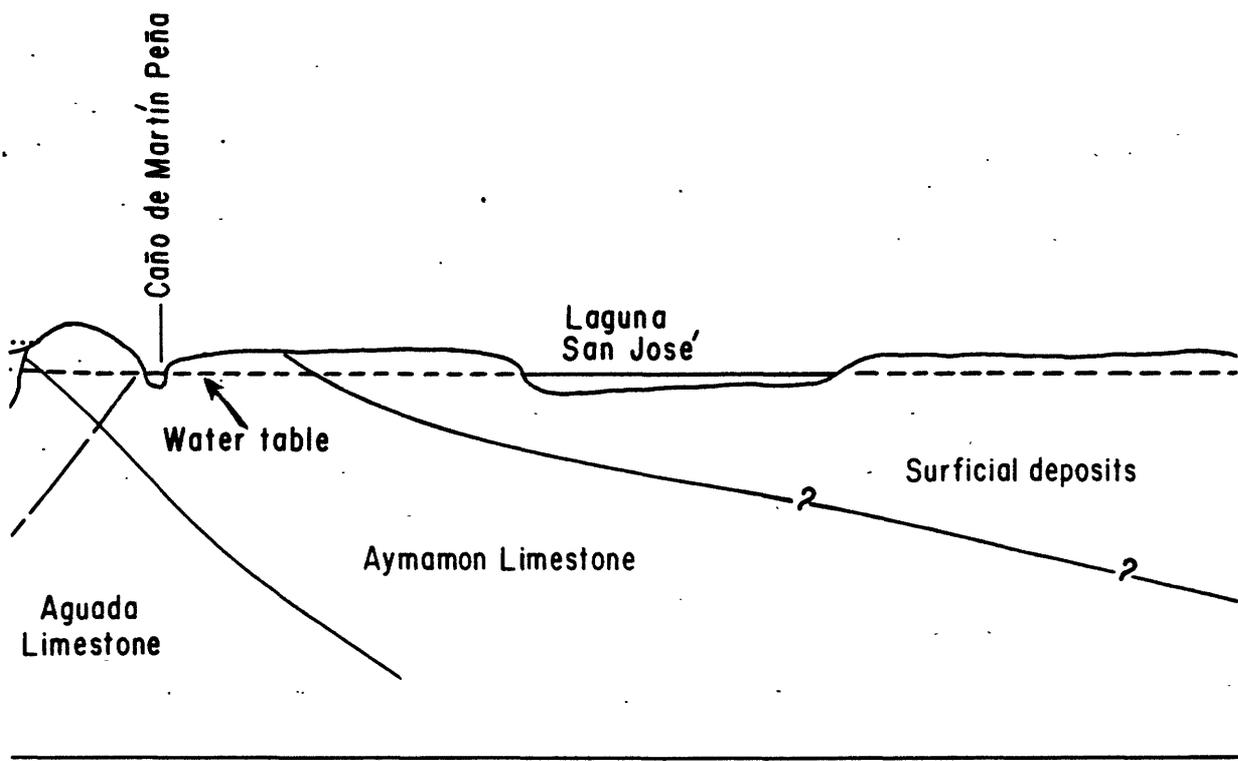
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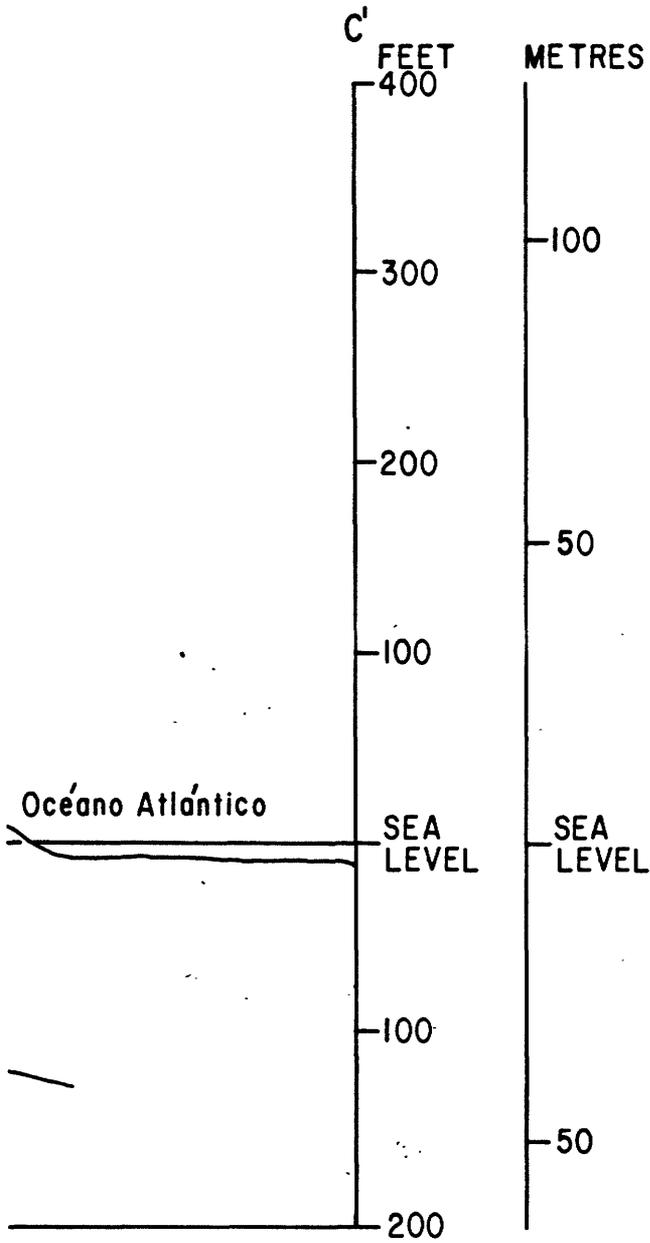
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3c-3

31



3c - 4

52

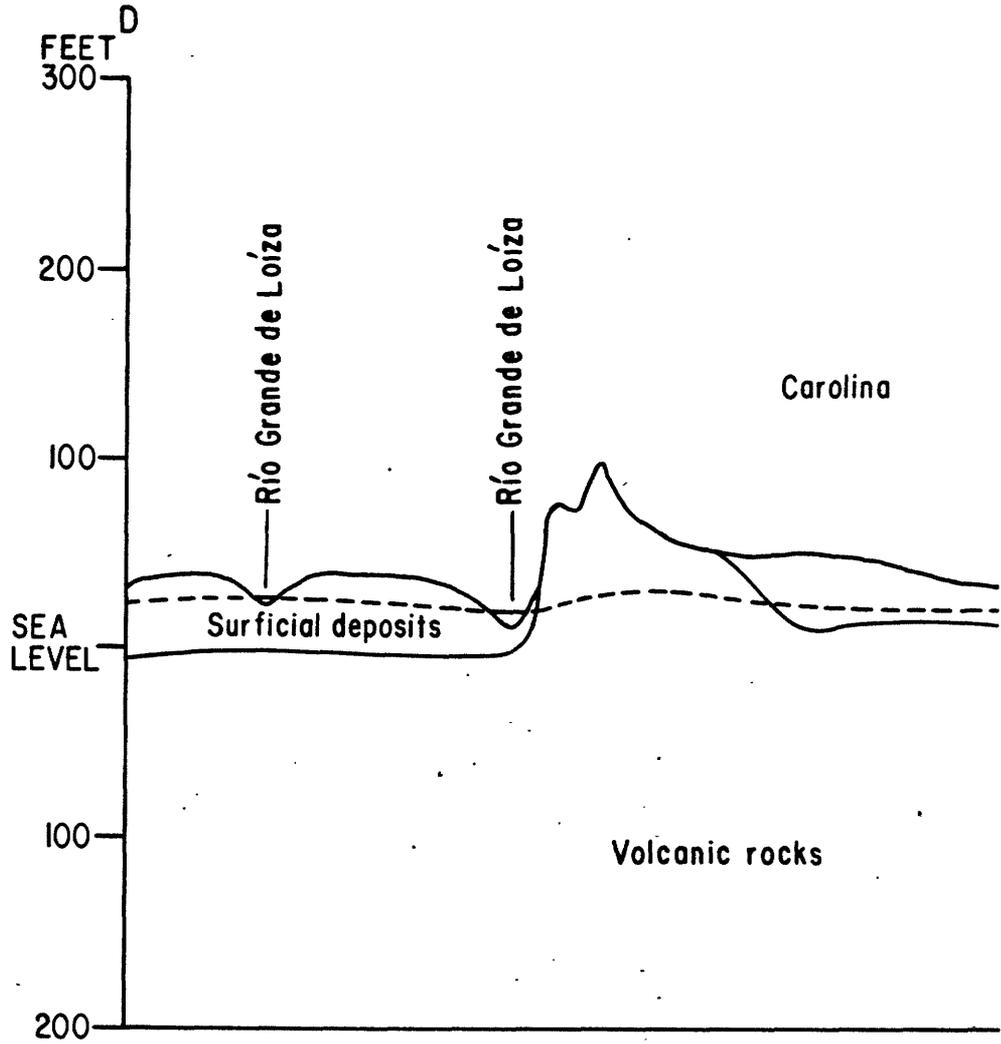
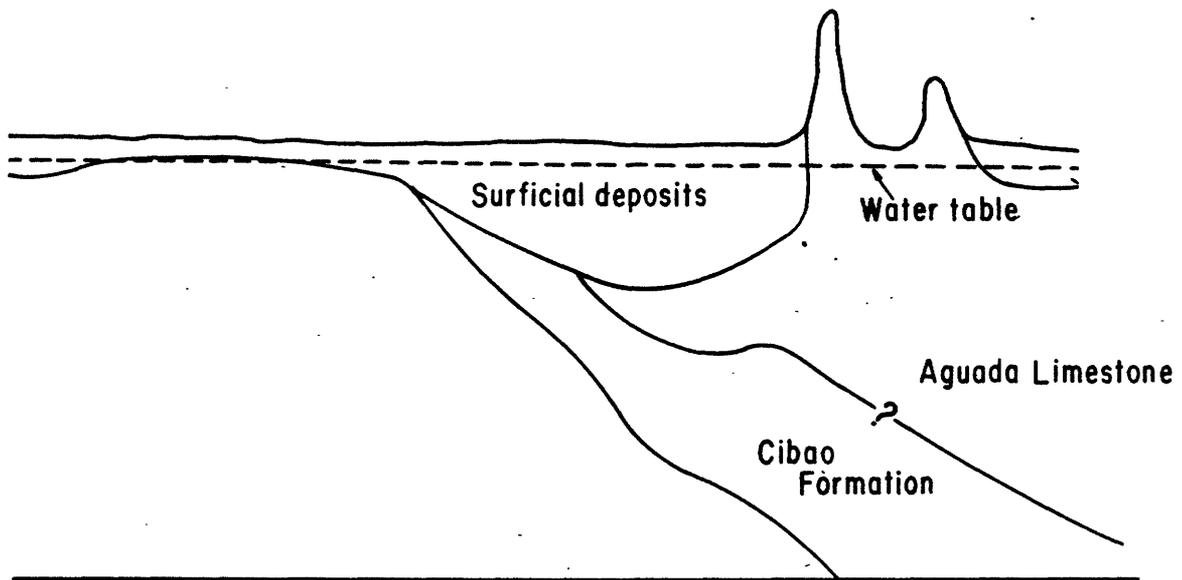


FIGURE 3c -- CROSS-SECTIONS

SEE LOCATION ON FIG. 3a

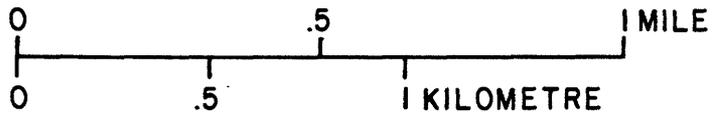
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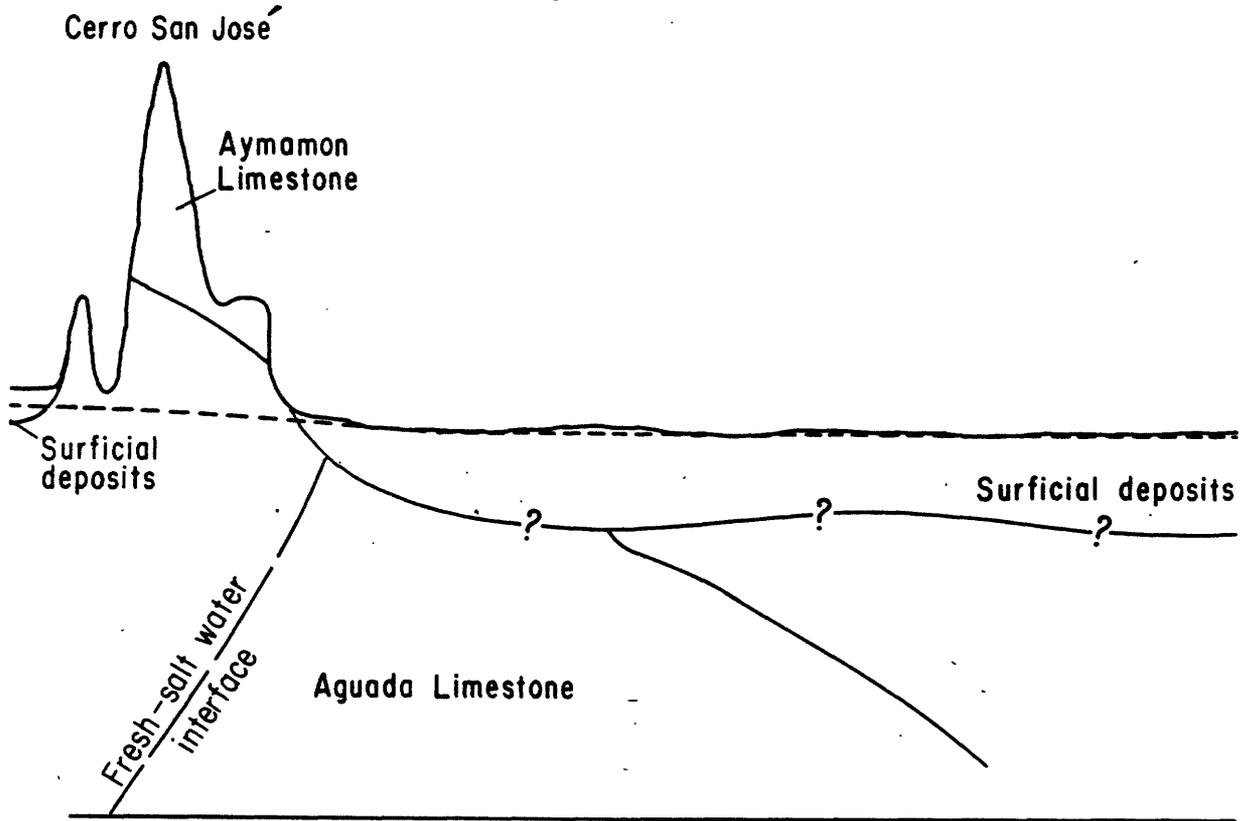
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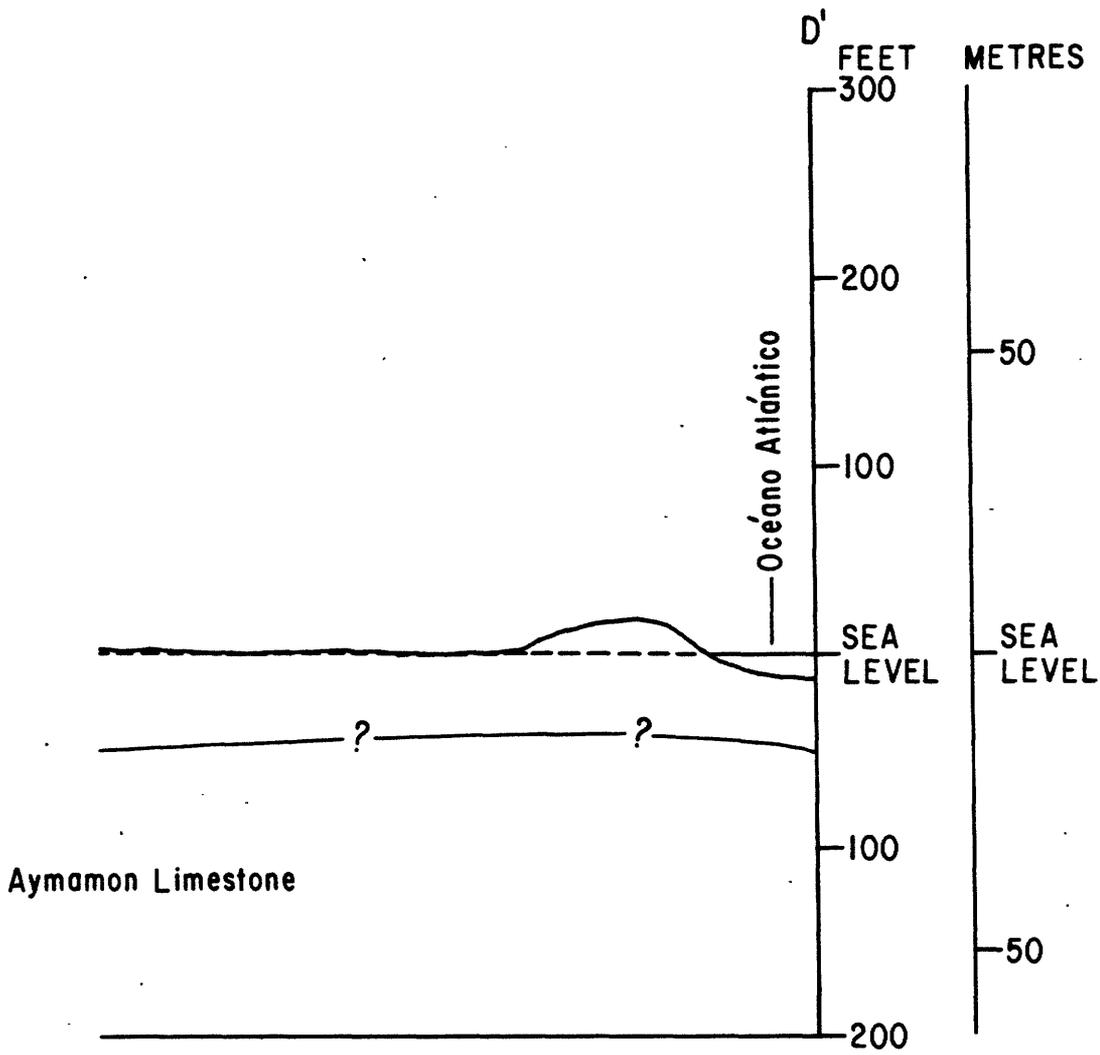
HORIZONTAL SCALE FOR BOTH SECTIONS

See fig 3a for definitions of the geologic formations



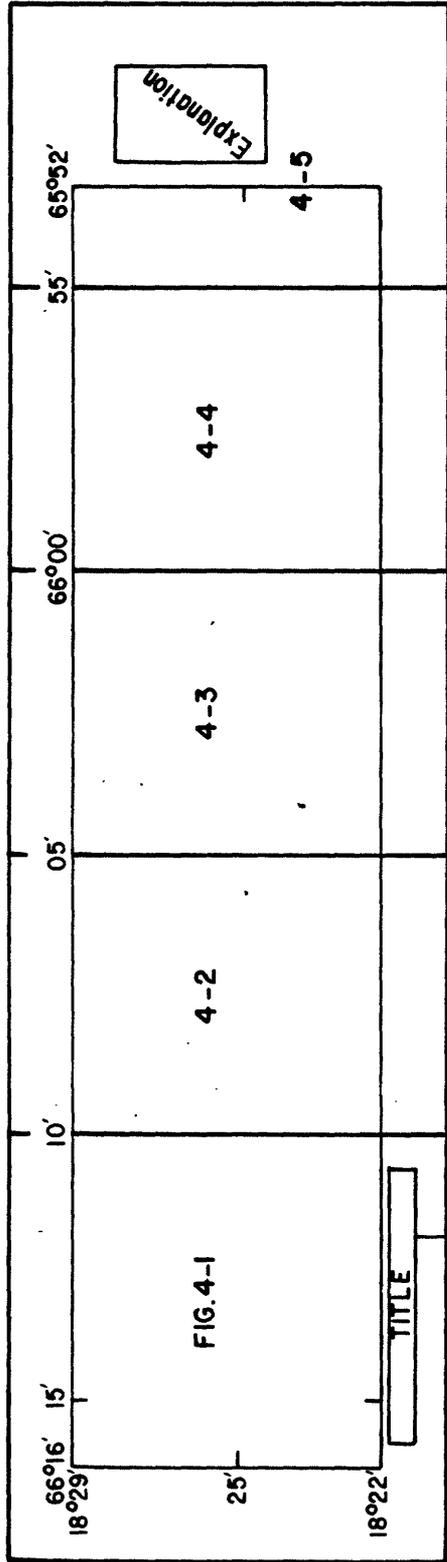
3c - 7

55

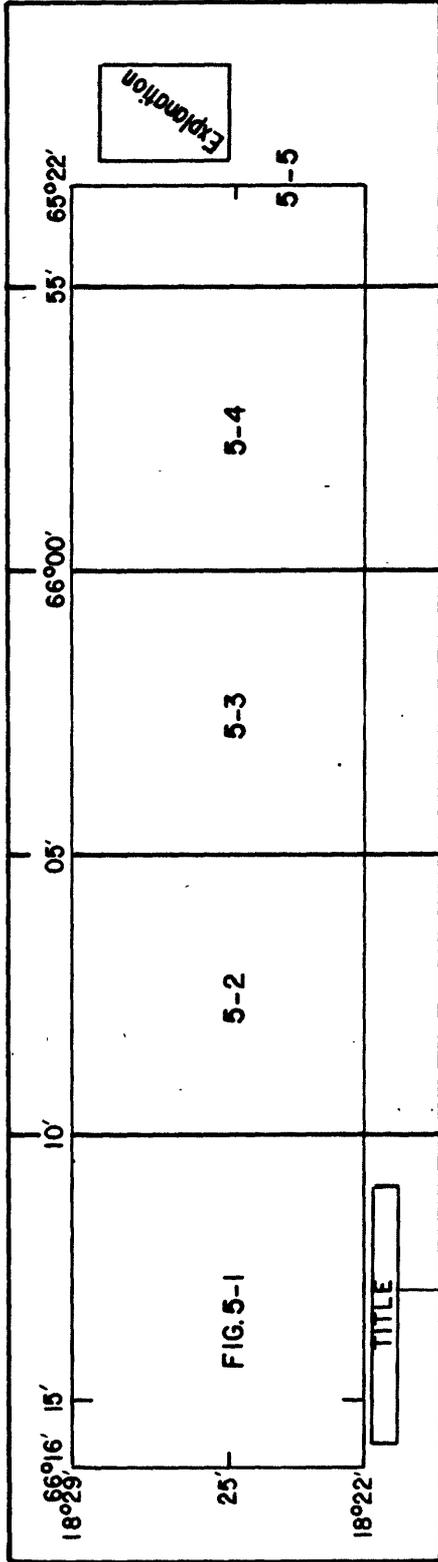


3c - 8

56



RELOCATED ON COMPONENT



RELOCATED ON COMPONENT

(FIGURES 4 AND 5 COMPOSE THIS 18"x24" PLATE)

57

074
11
00

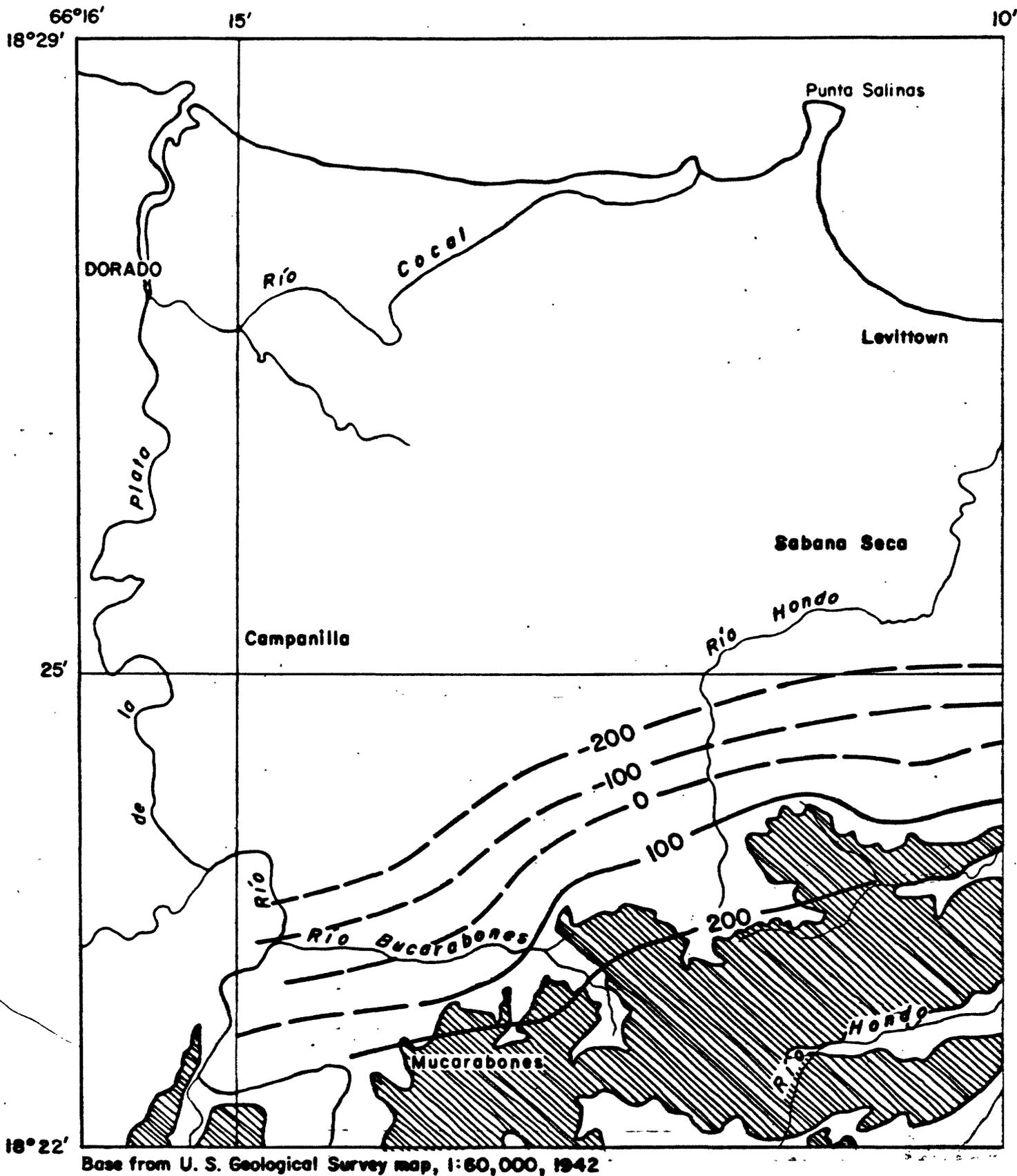
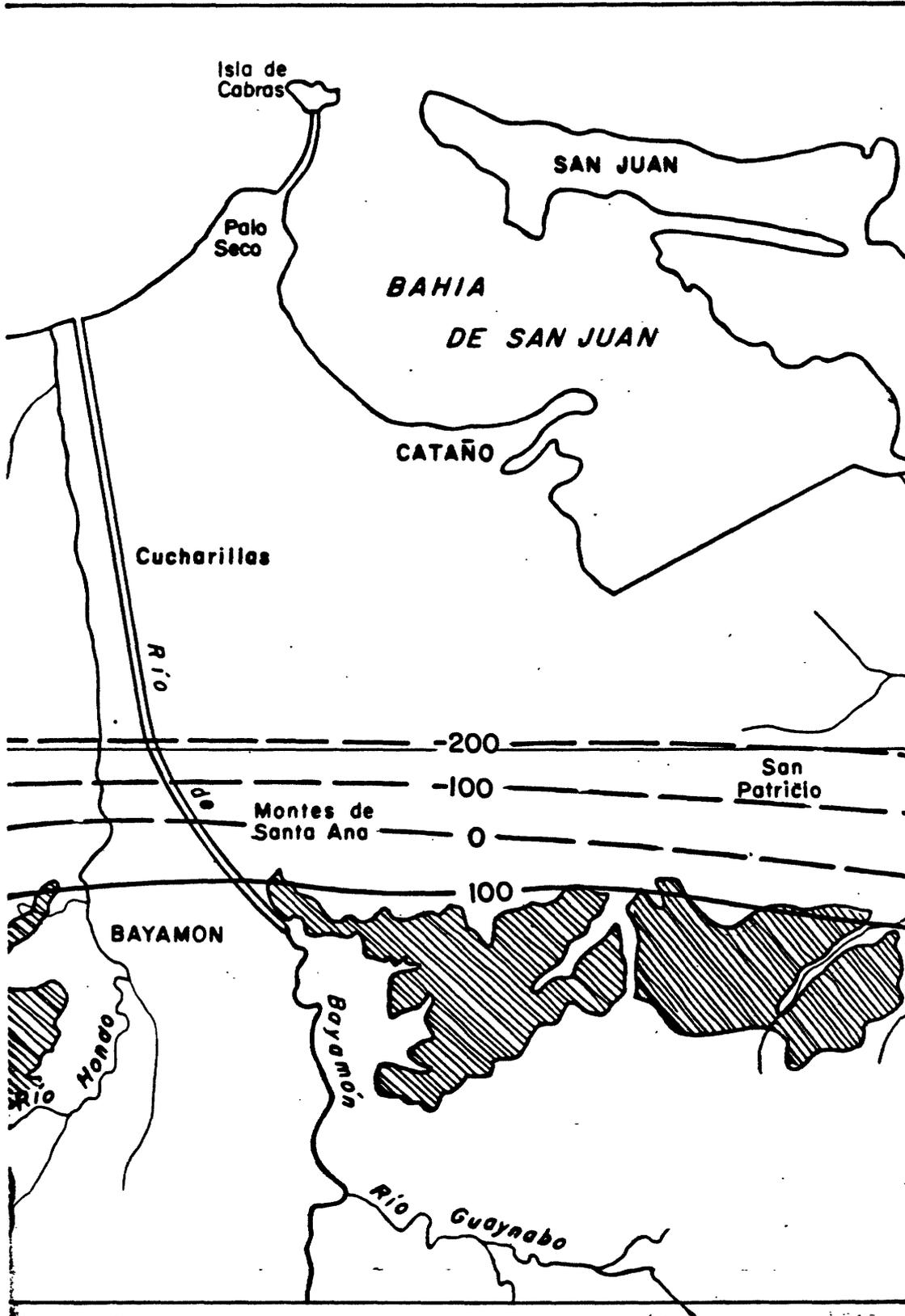
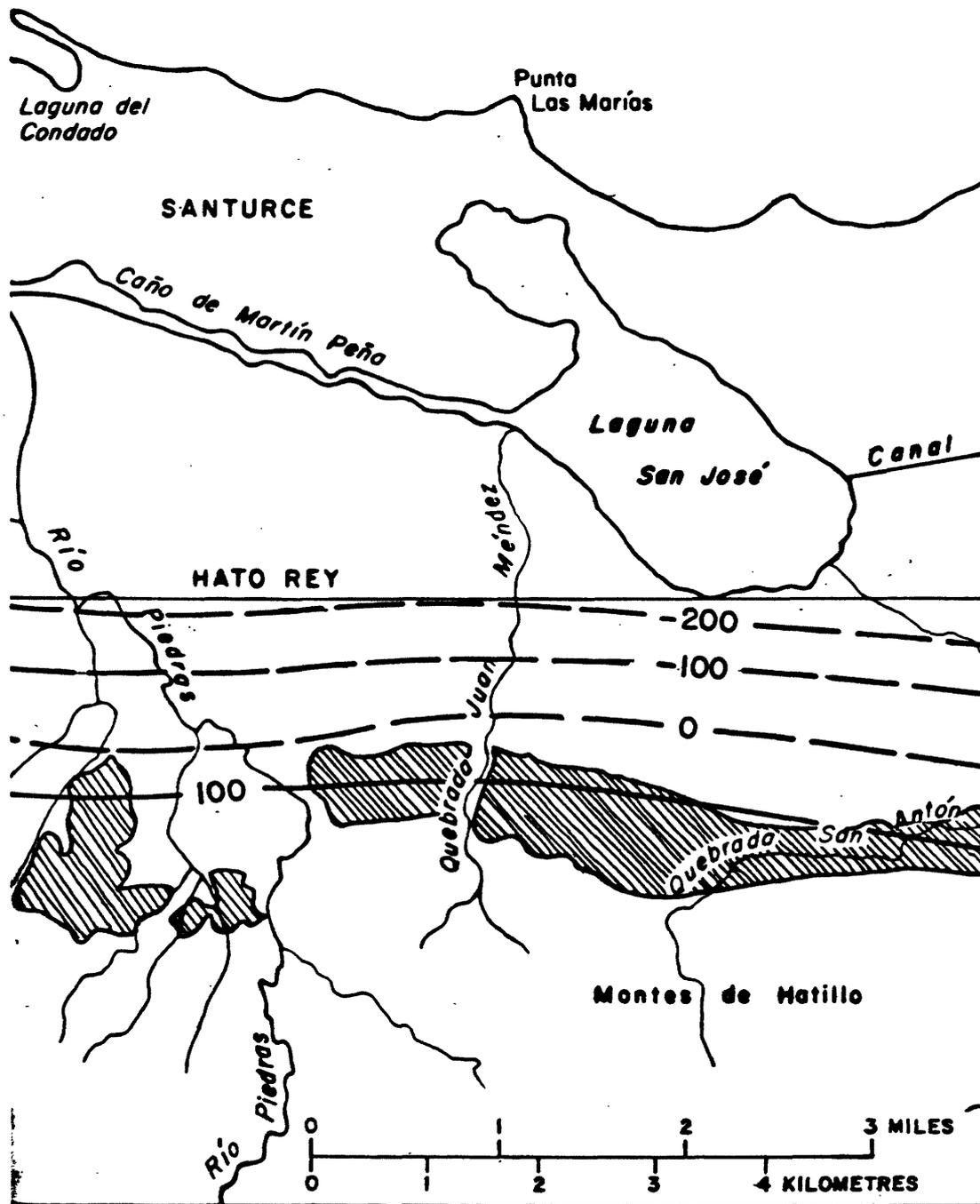
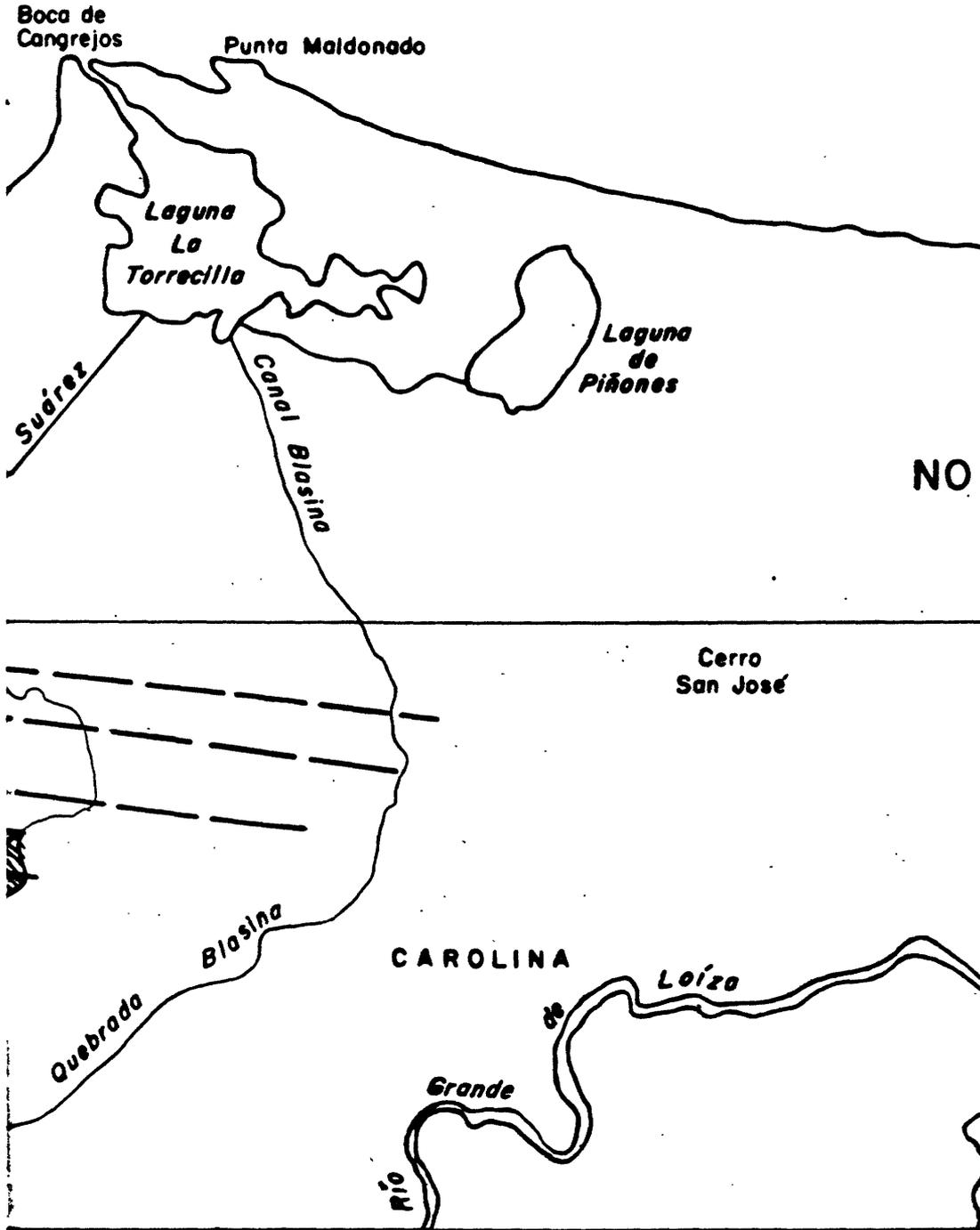


FIGURE 4 -- OUTCROP AREAS AND ALTITUDE OF THE TOP OF THE SAN SEBASTIAN FORMATION.



OCEANO ATLANTICO





NO

Cerro San José

CAROLINA

Loíza

Río Grande

Quebrada Blasina

Suárez

Canal Blasina

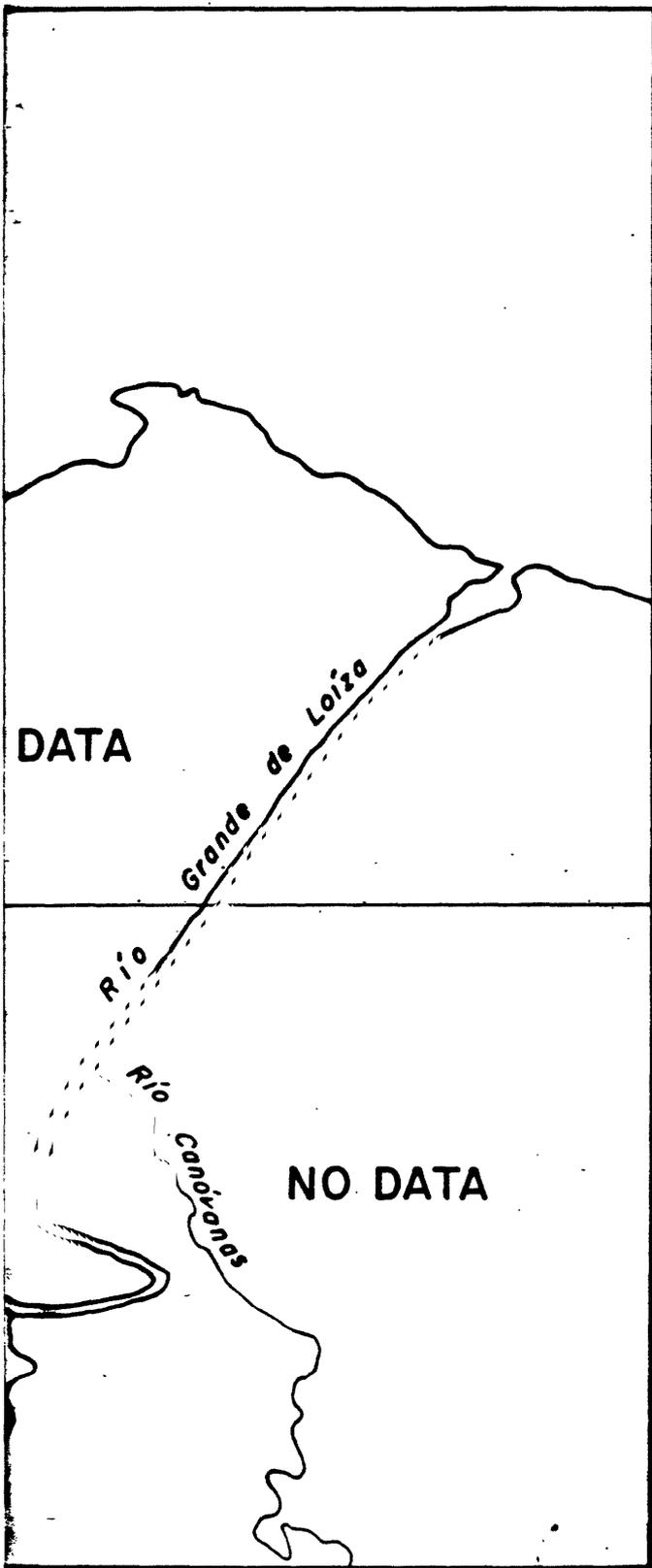
Laguna La Torrecilla

Laguna de Piñones

Boca de Cangrejos

Punta Maldonado

61



EXPLANATION



Area of outcrop

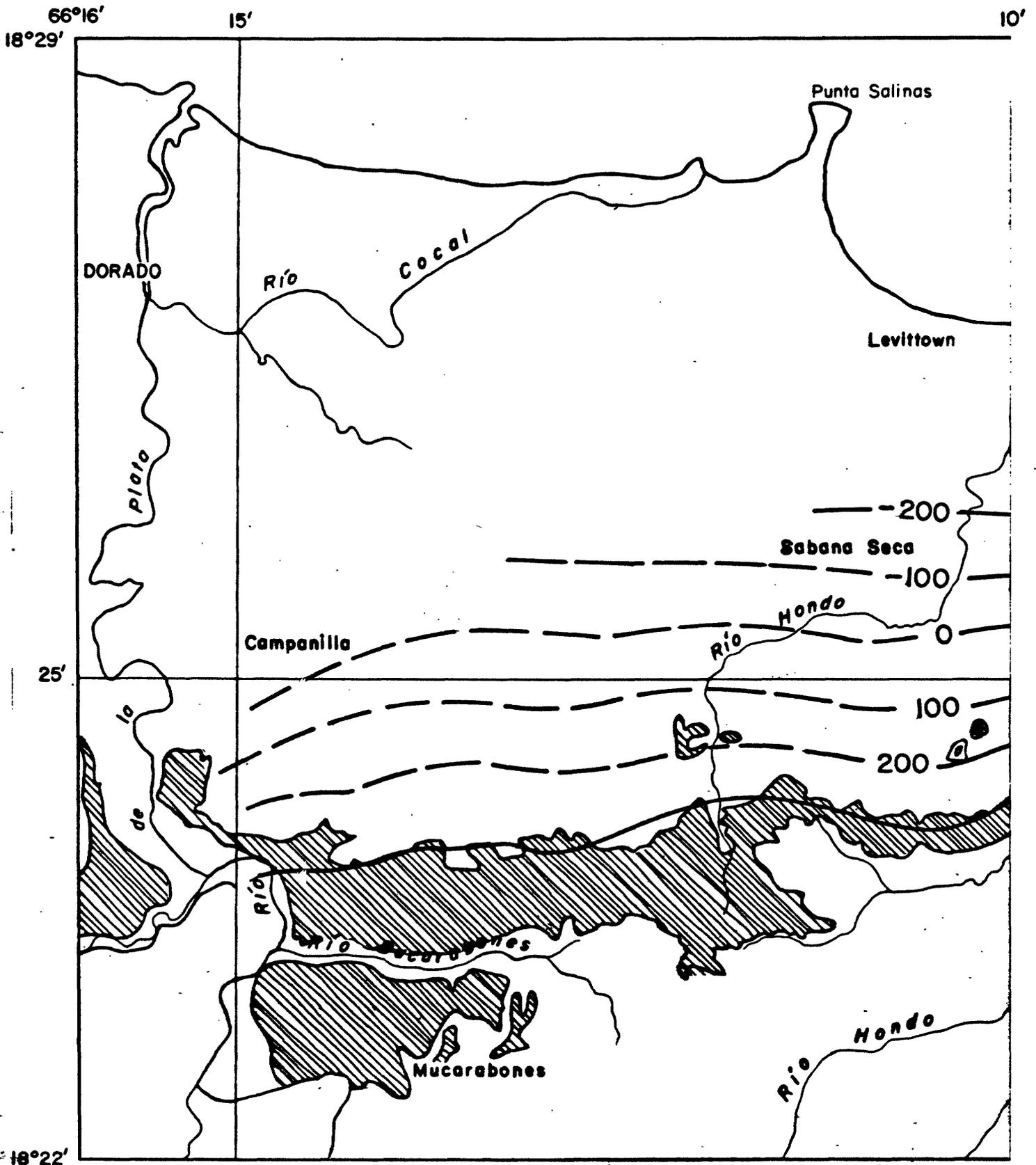
— 100 —

STRUCTURE CONTOUR

Shows altitude of top of San Sebastian Formation. Dashed where approximately located. Contour interval 100 feet (30 metres). Datum is mean sea level.

DATA

NO DATA

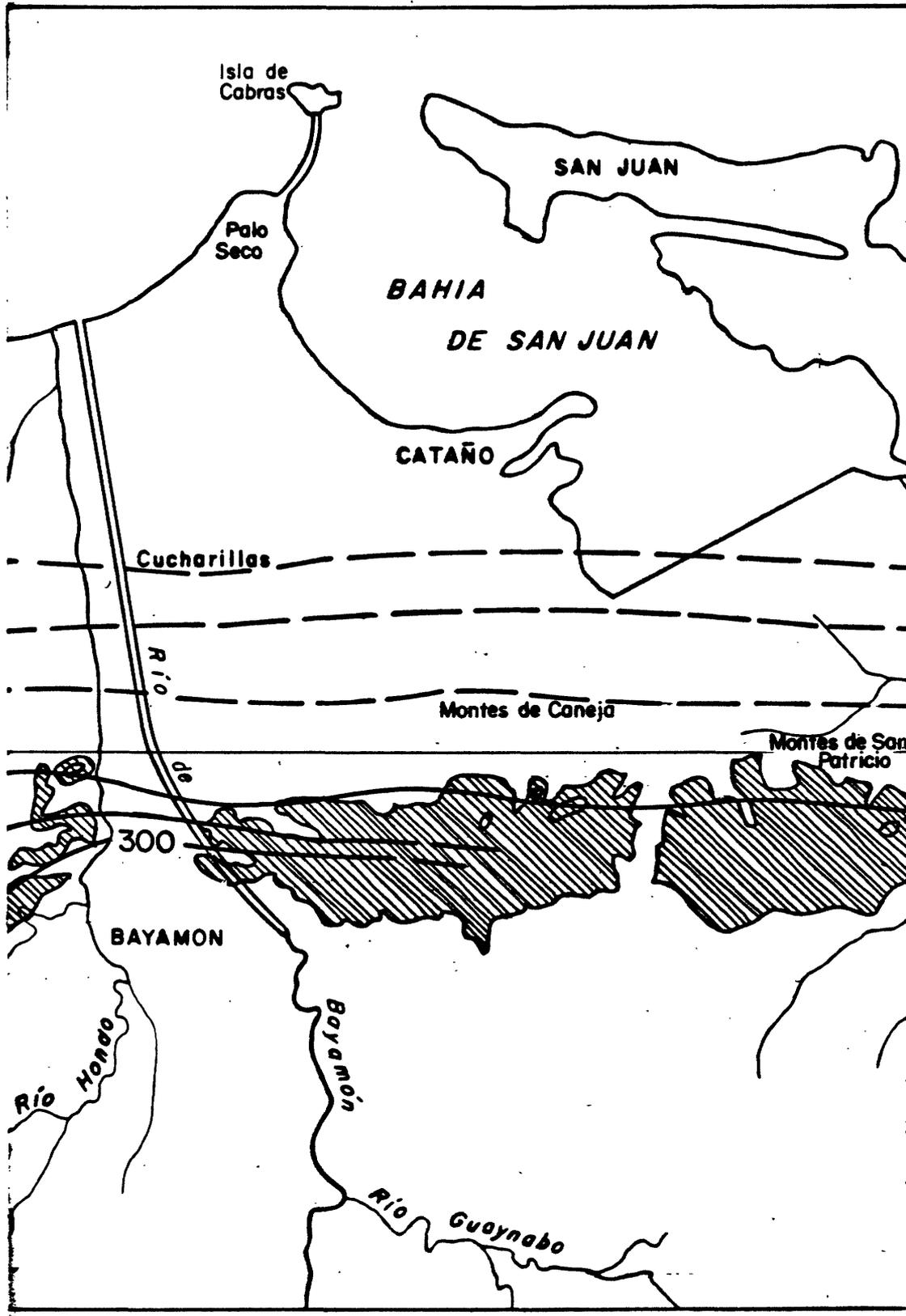


Base from U. S. Geological Survey map, 1:80,000, 1942

FIGURE 5 -- OUTCROP AREAS AND ALTITUDE OF THE TOP OF THE CIBAO FORMATION.

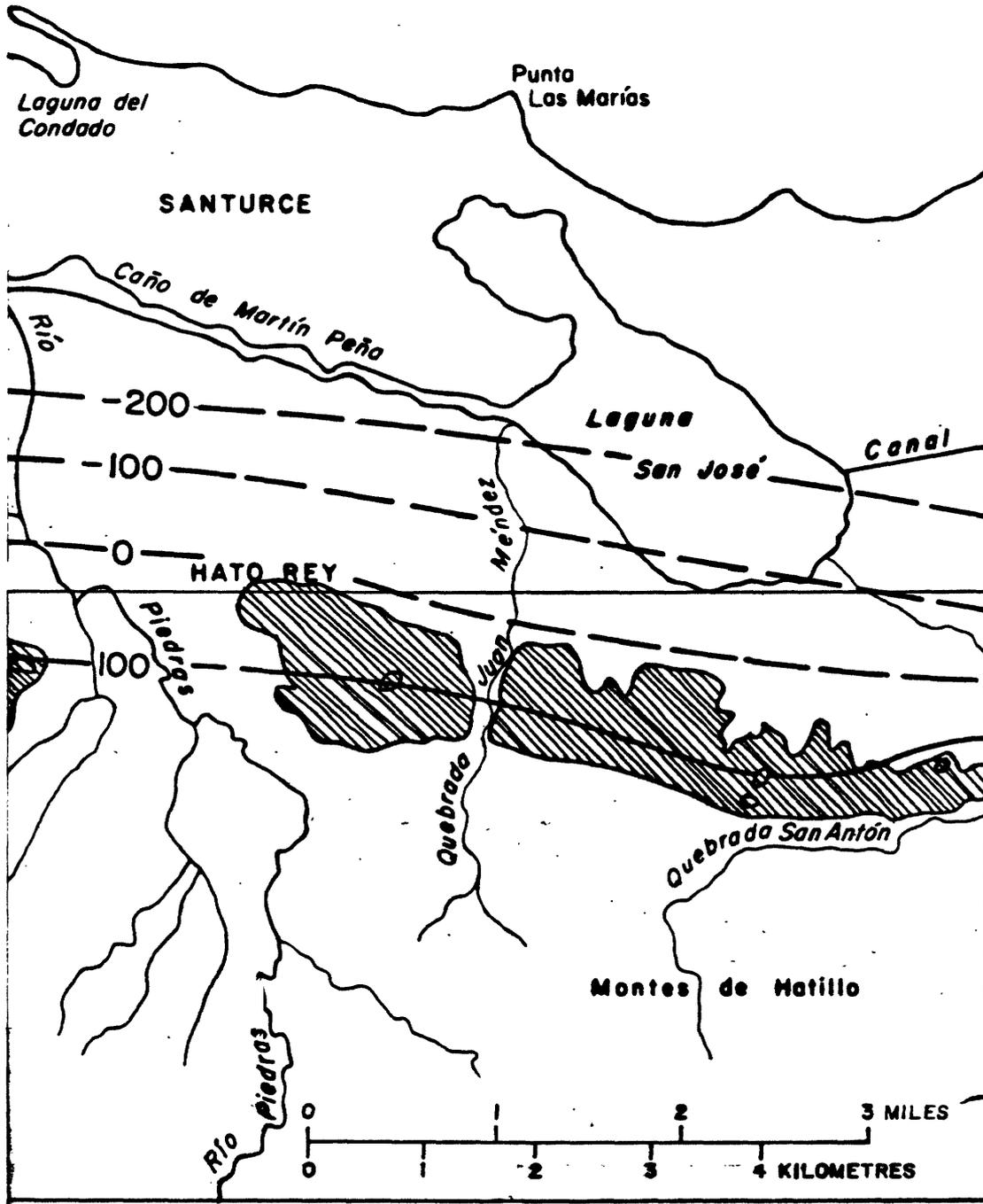
5-1

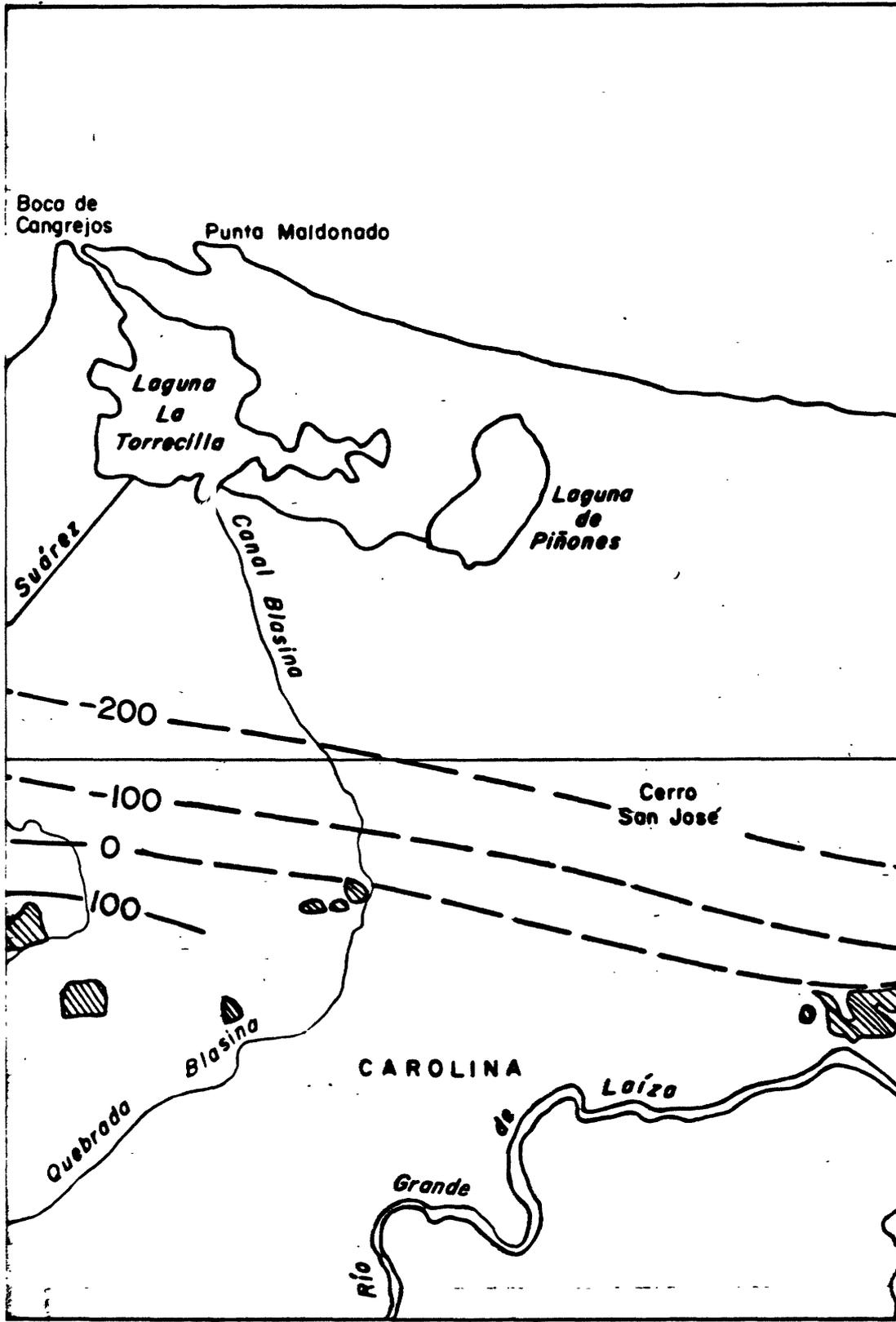
65



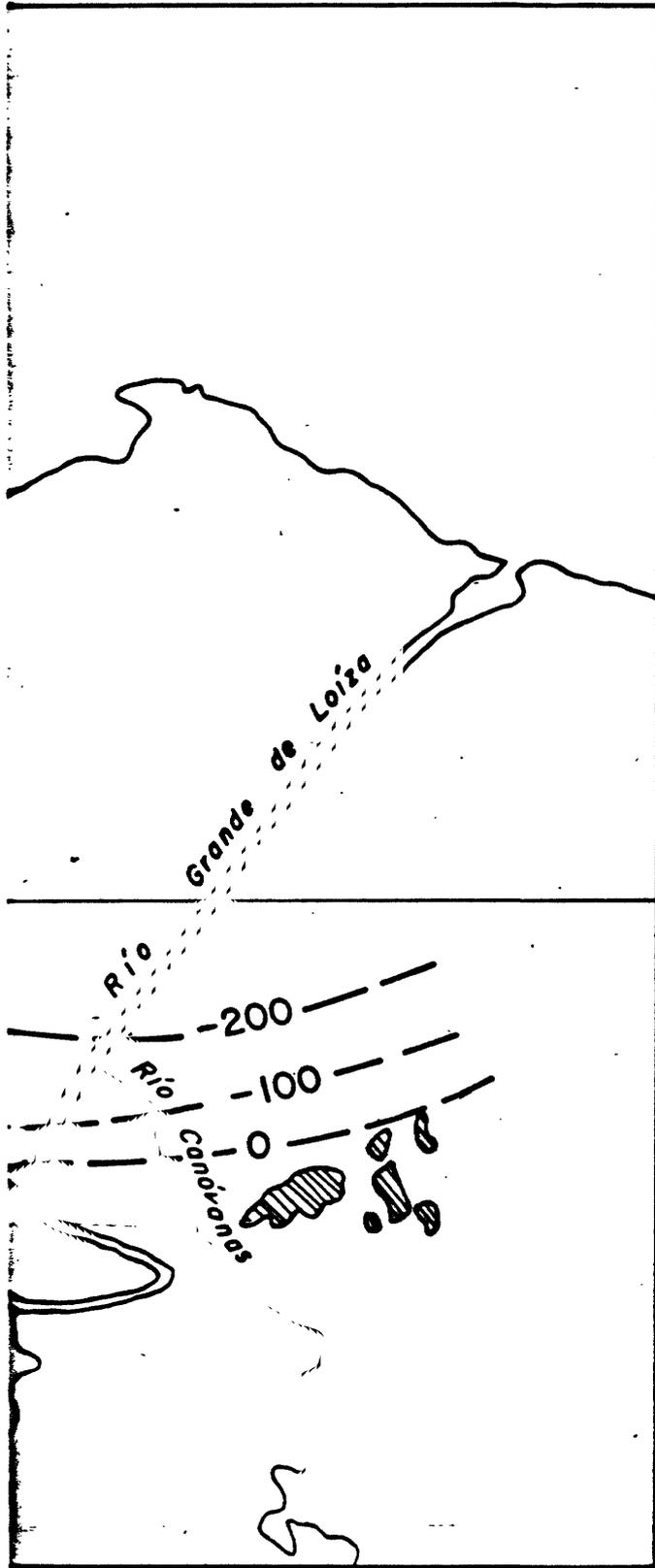
64

OCEANO ATLANTICO





65°52'



EXPLANATION



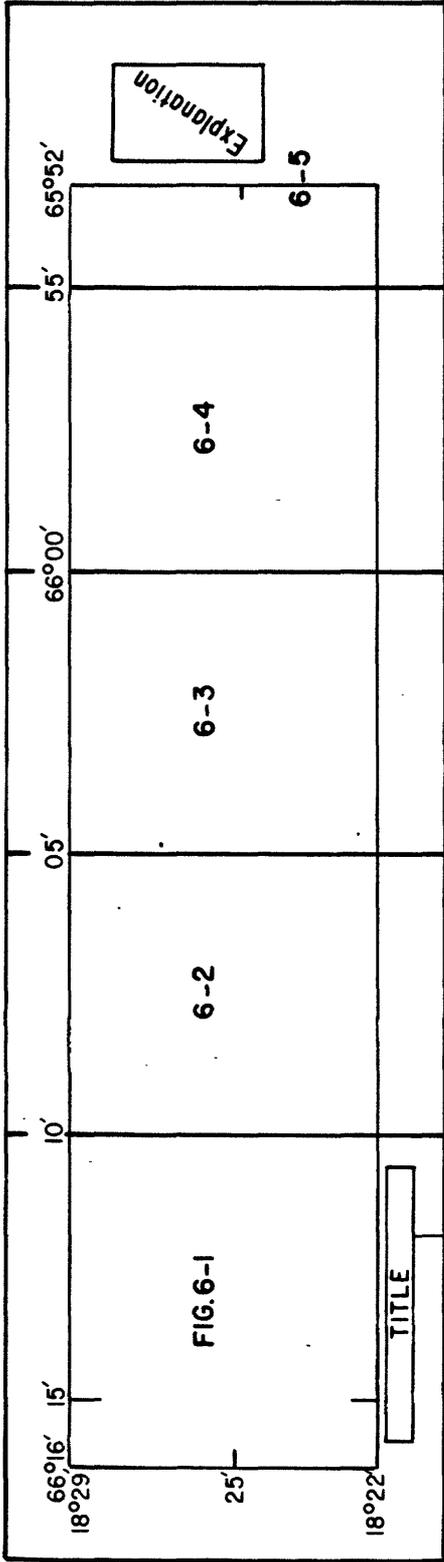
Area of outcrop



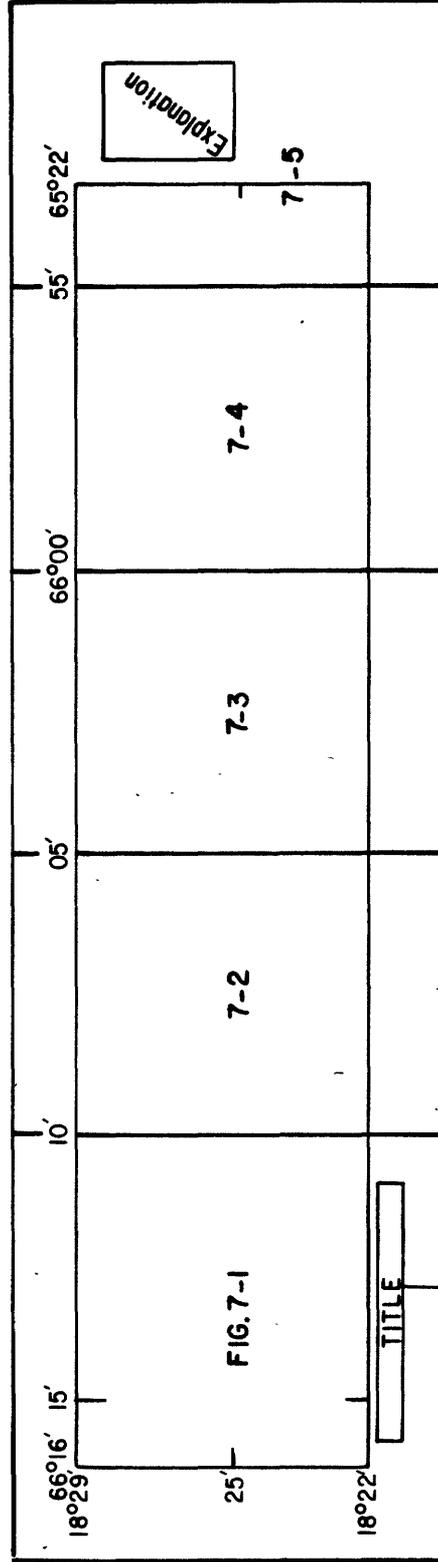
STRUCTURE CONTOUR-

Shows altitude of top of Cibao Formation. Dashed where approximately located. Contour 100 feet (30 metres). Datum is mean sea level

67



RELOCATED ON COMPONENT

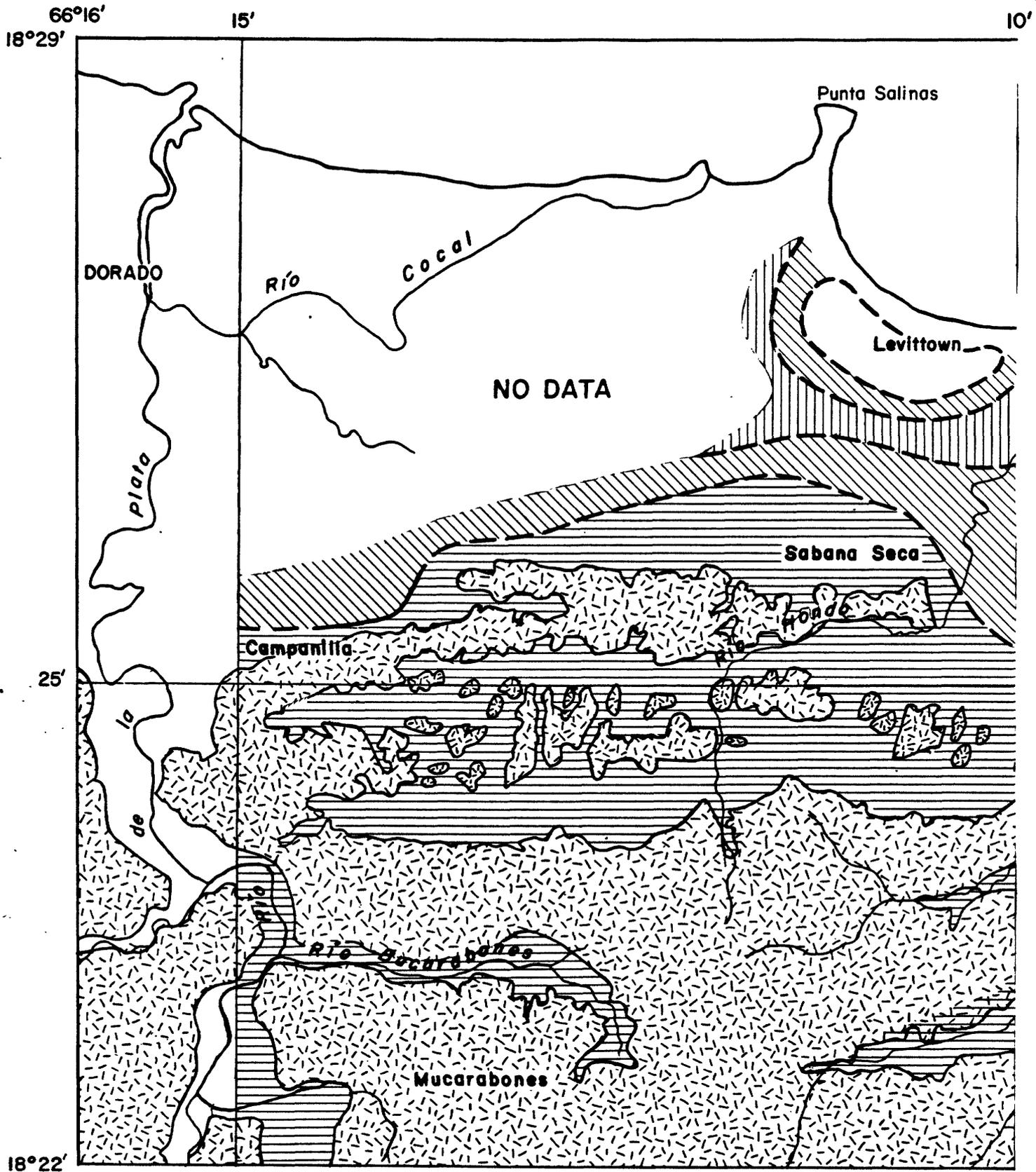


RELOCATED ON COMPONENT

(FIGURES 6 AND 7 COMPOSE THIS 18" x 24" PLATE)

7-0
6-0

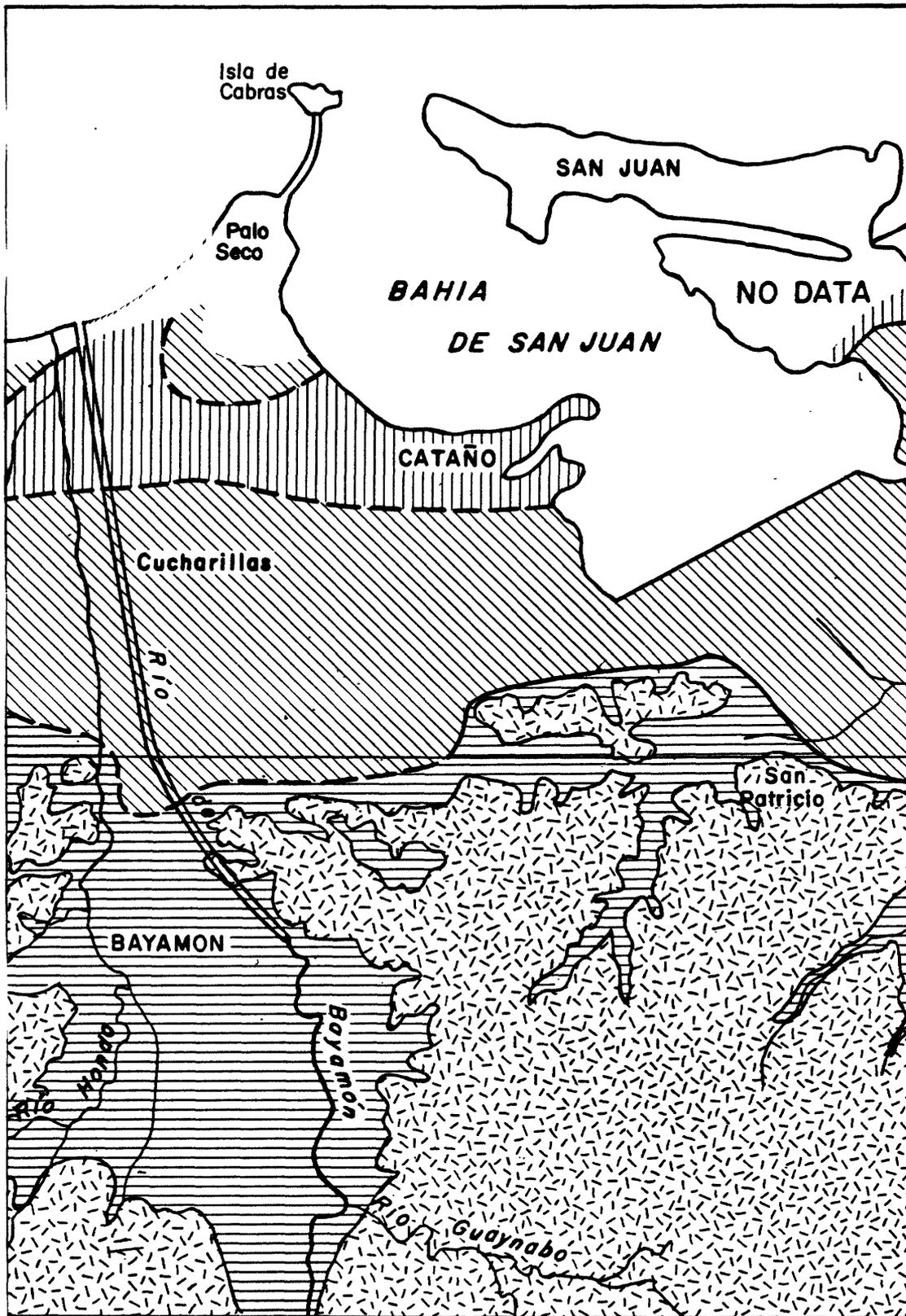
68

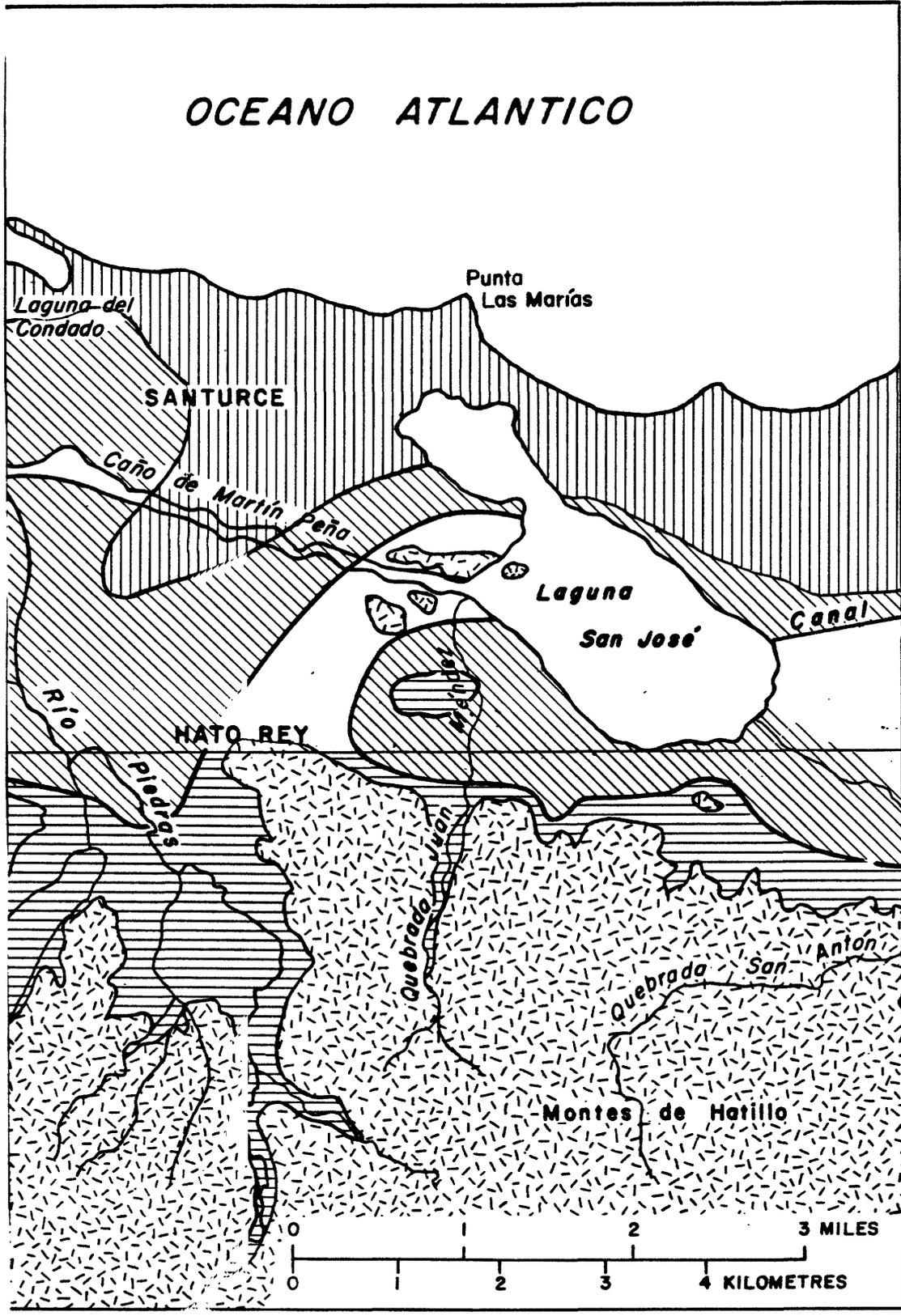


Base from U. S. Geological Survey map, 1:60,000, 1942

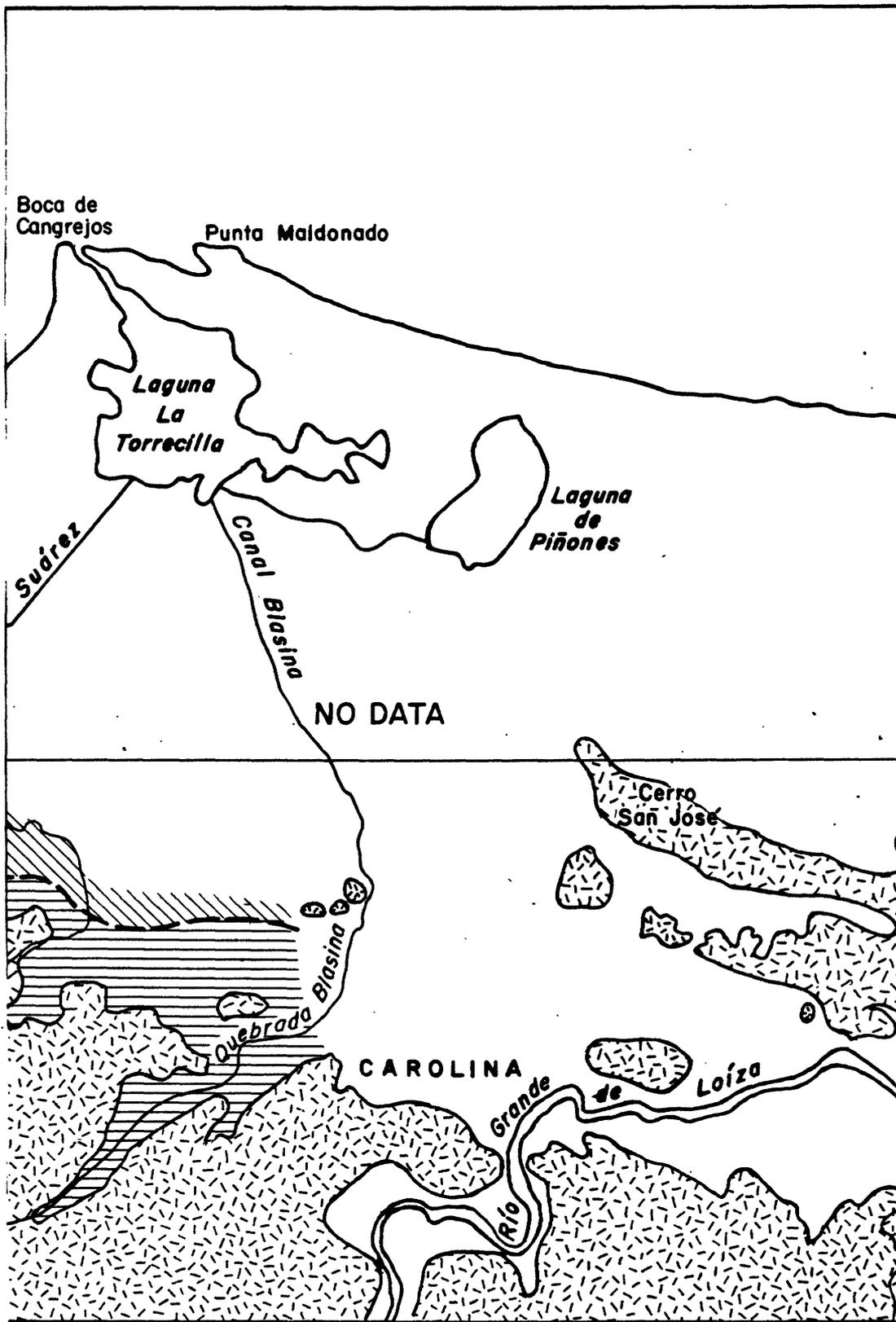
FIGURE 6-- THICKNESS OF SURFICIAL DEPOSITS IN THE SAN JUAN AREA.

6-1 69

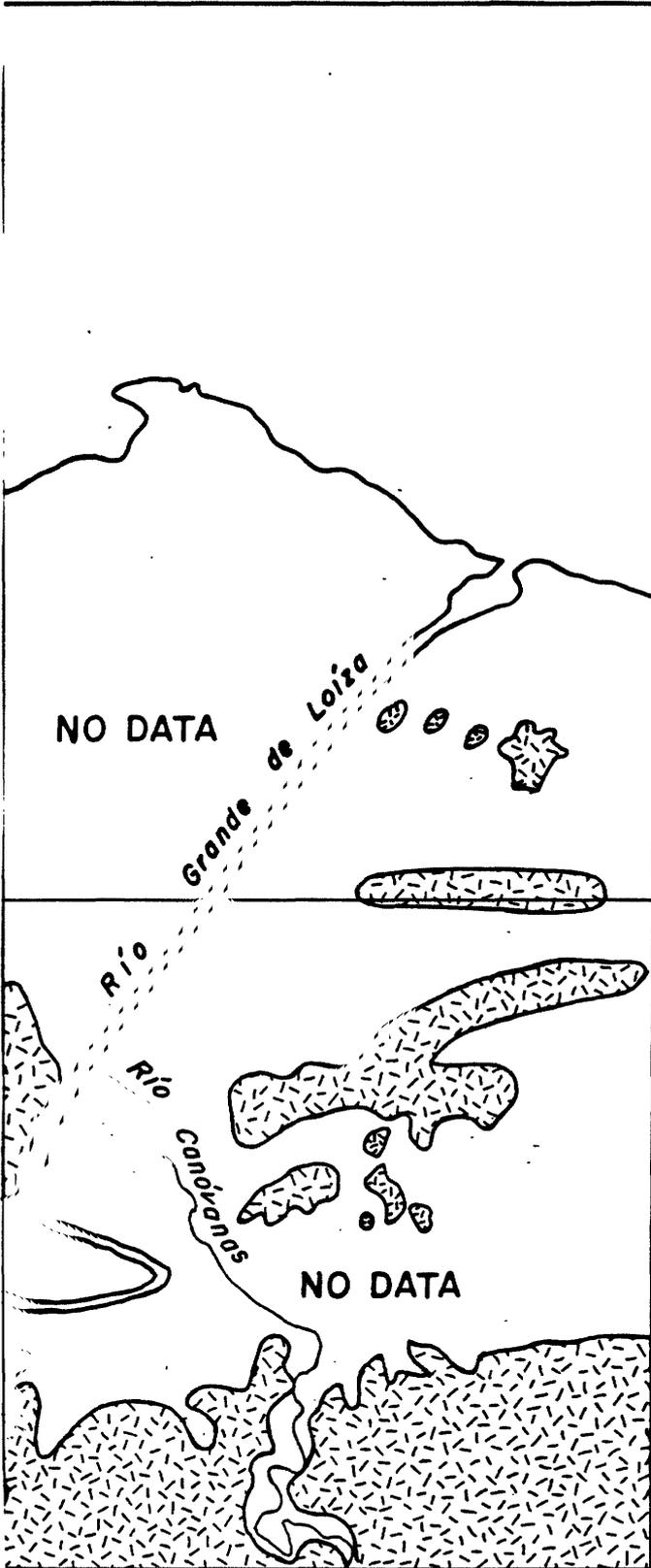




71

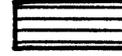


72



EXPLANATION

Thickness of surficial deposits, in feet (metres)



Less than 50 (15)



50 to 100 (15 to 30)

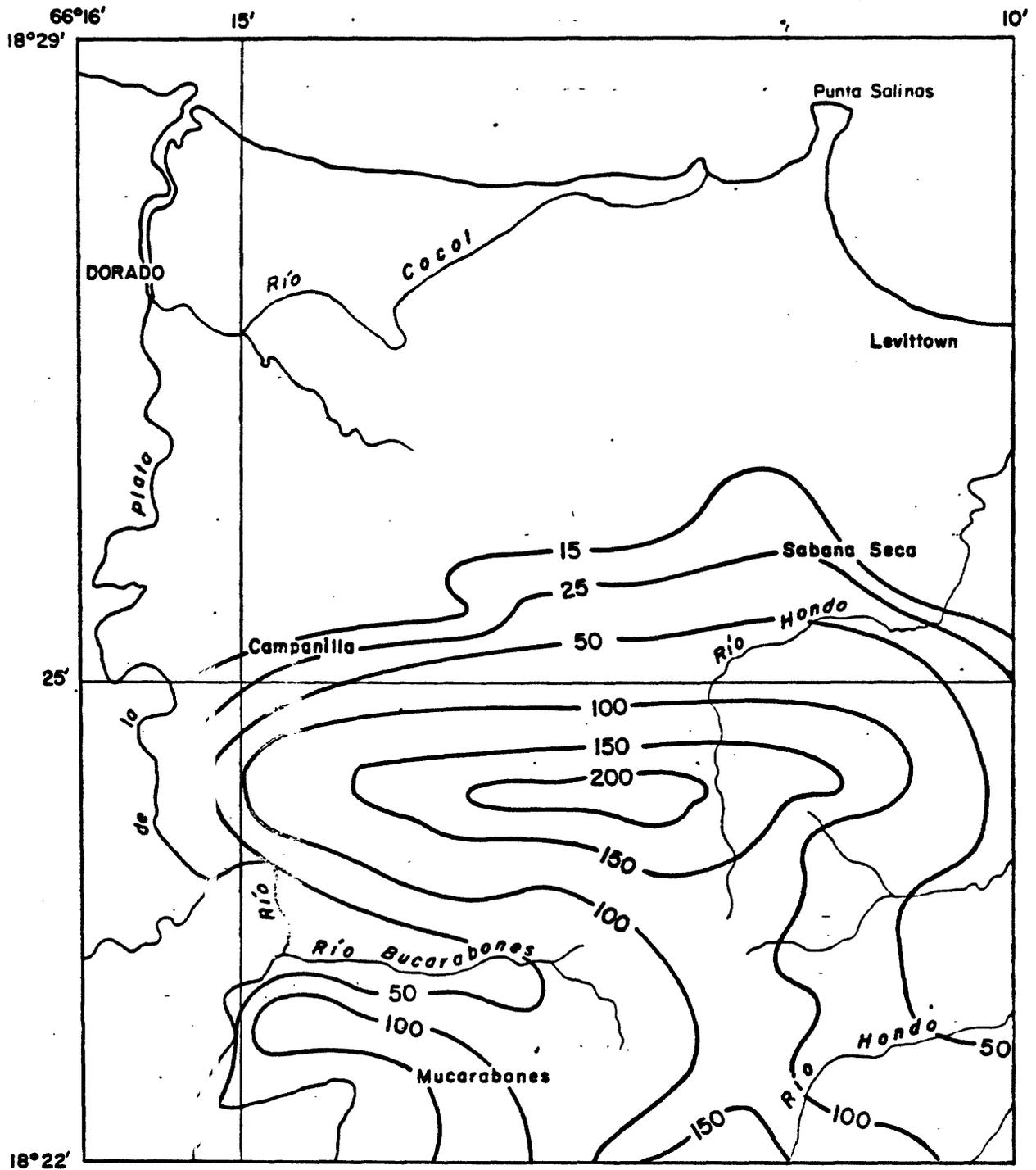


Greater than 100 (30)



Bedrock

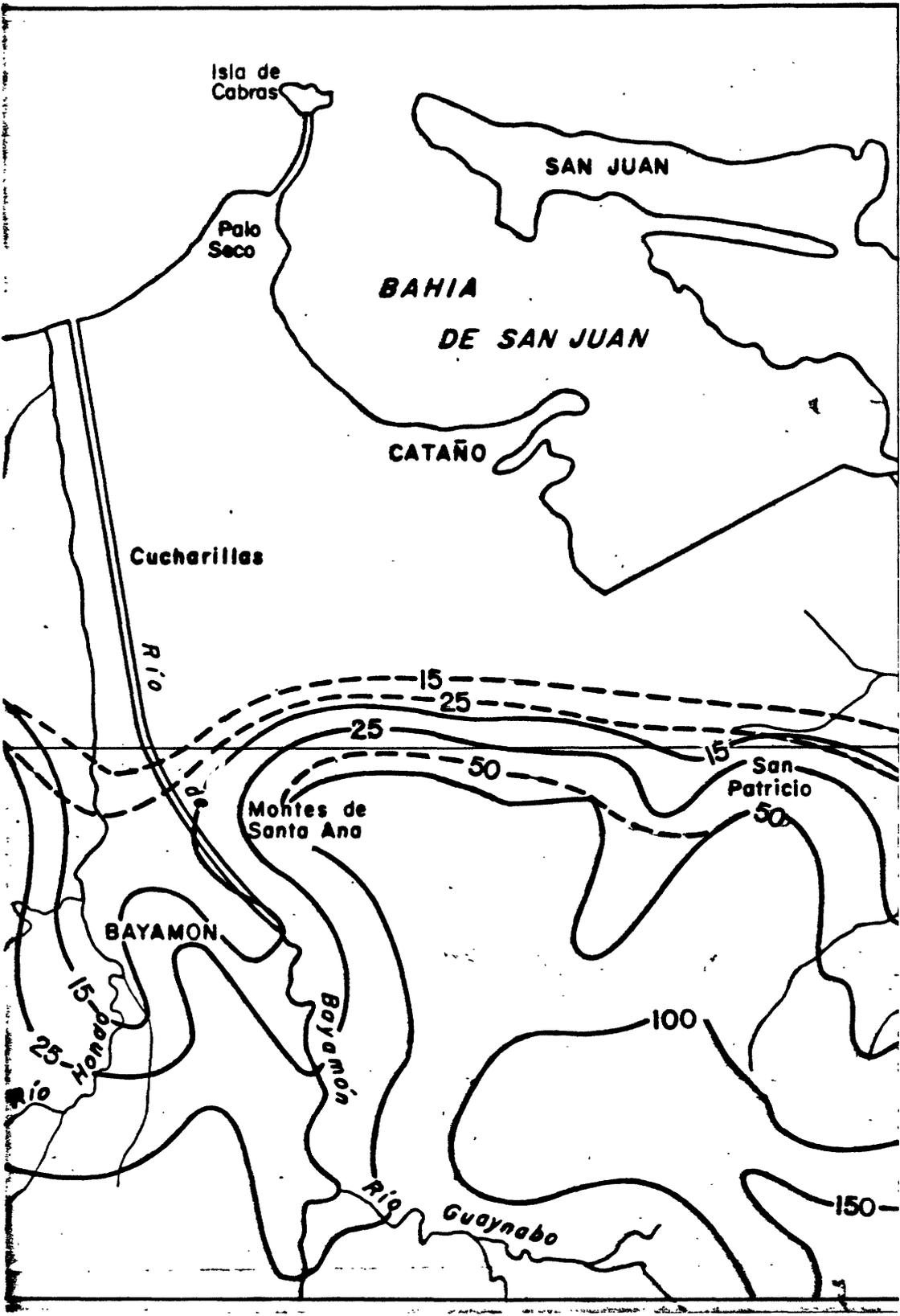
Contact, dashed where undefined



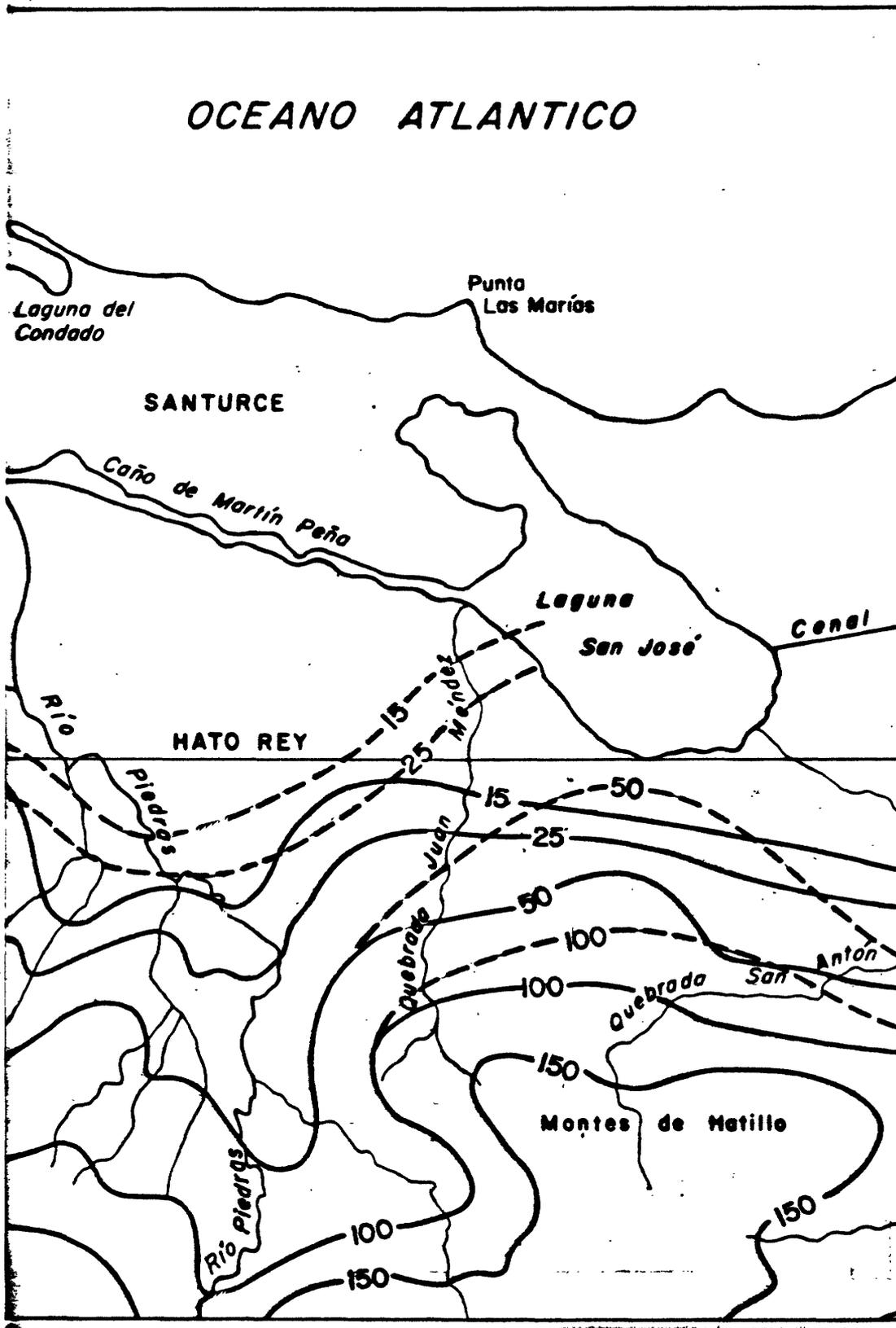
Base from U. S. Geological Survey map, 1:60,000, 1942

FIGURE 7 -- GENERALIZED CONFIGURATION OF THE WATER SURFACE OF THE UNCONFINED AQUIFER AND THE POTENTIOMETRIC SURFACE OF THE CONFINED AQUIFER IN THE SAN JUAN AREA.

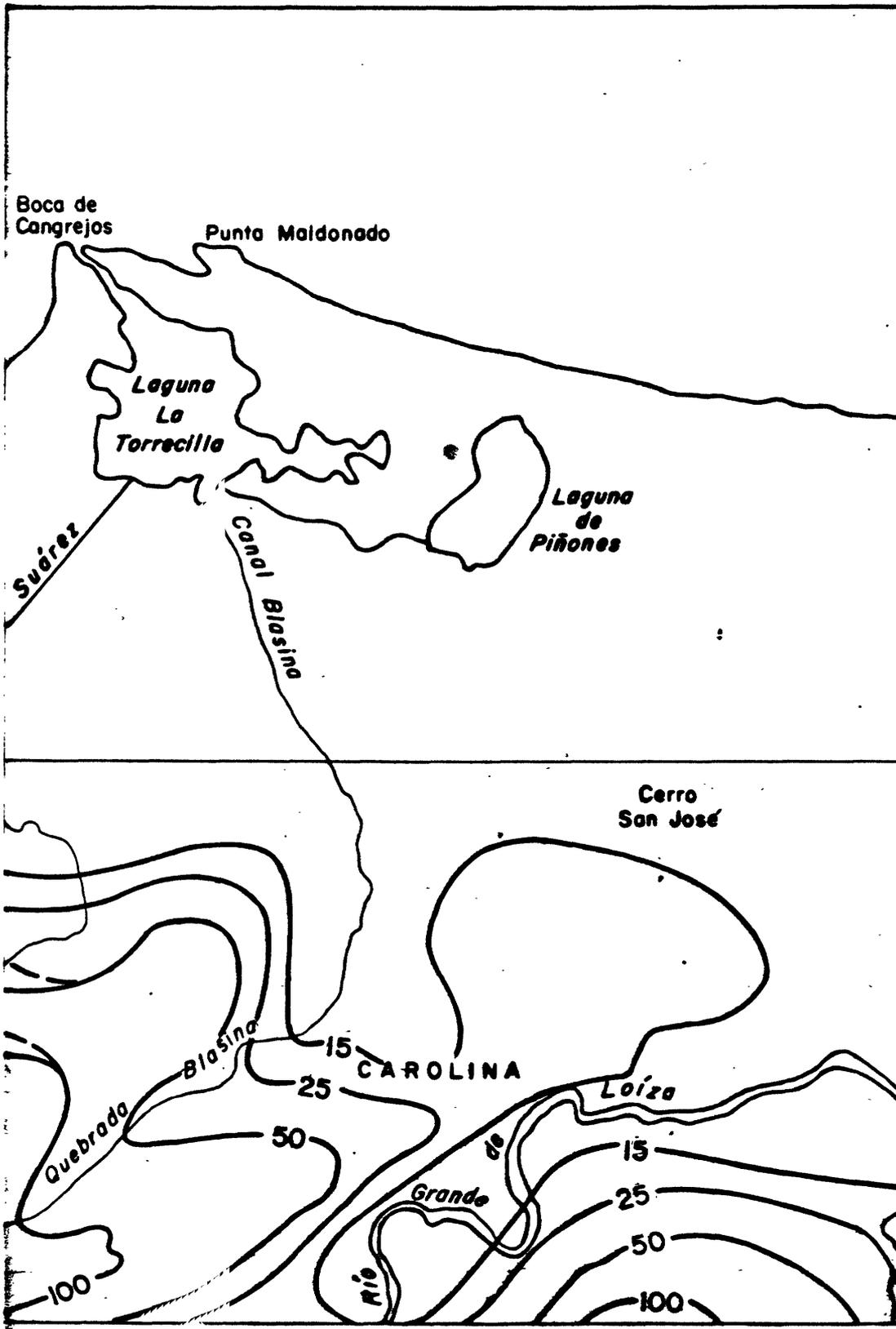
74
7-1



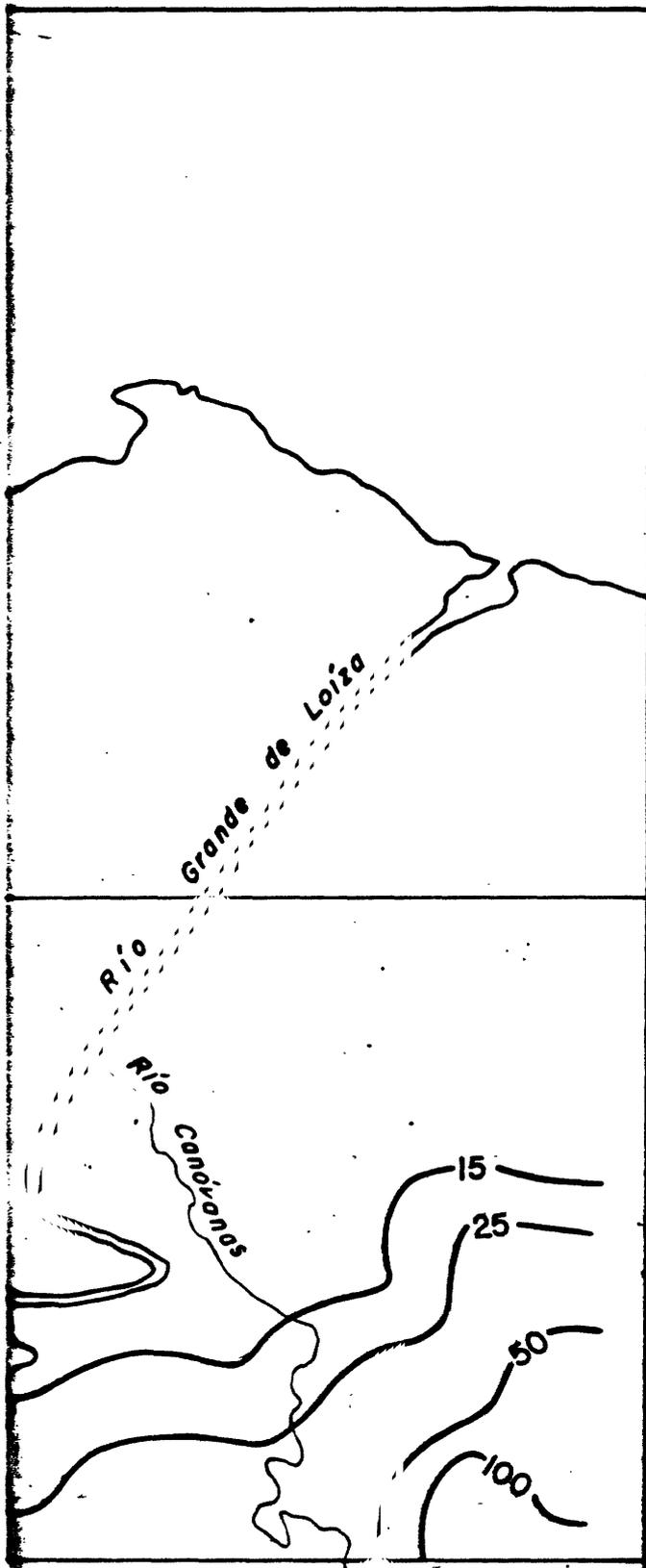
75



76



77



EXPLANATION

———15———

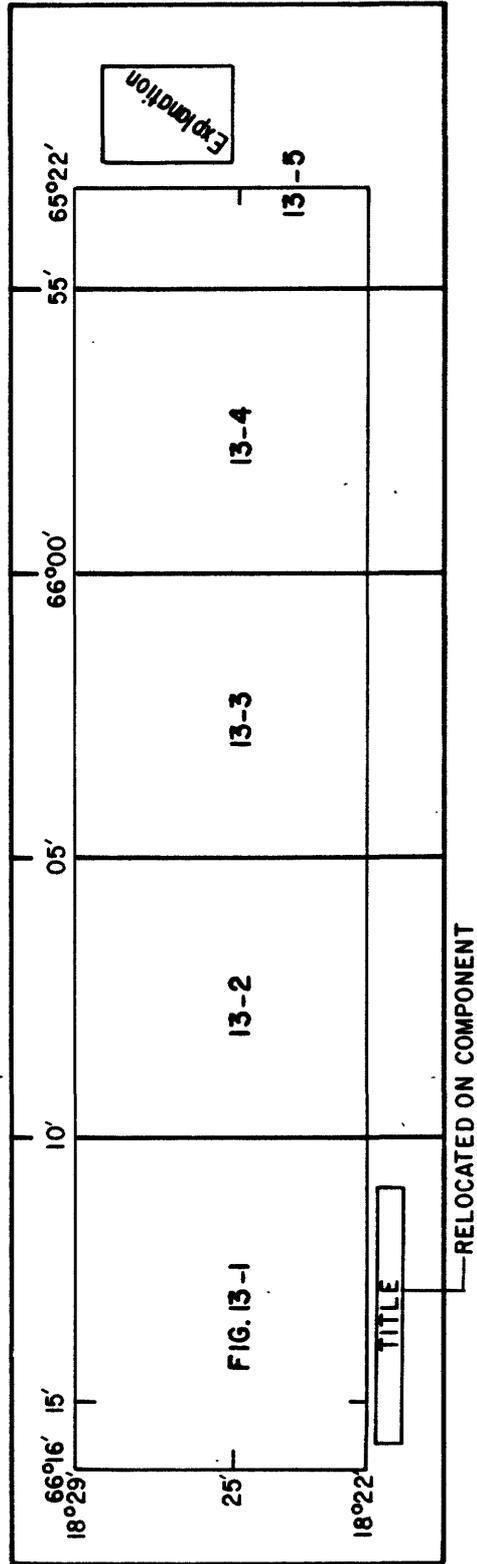
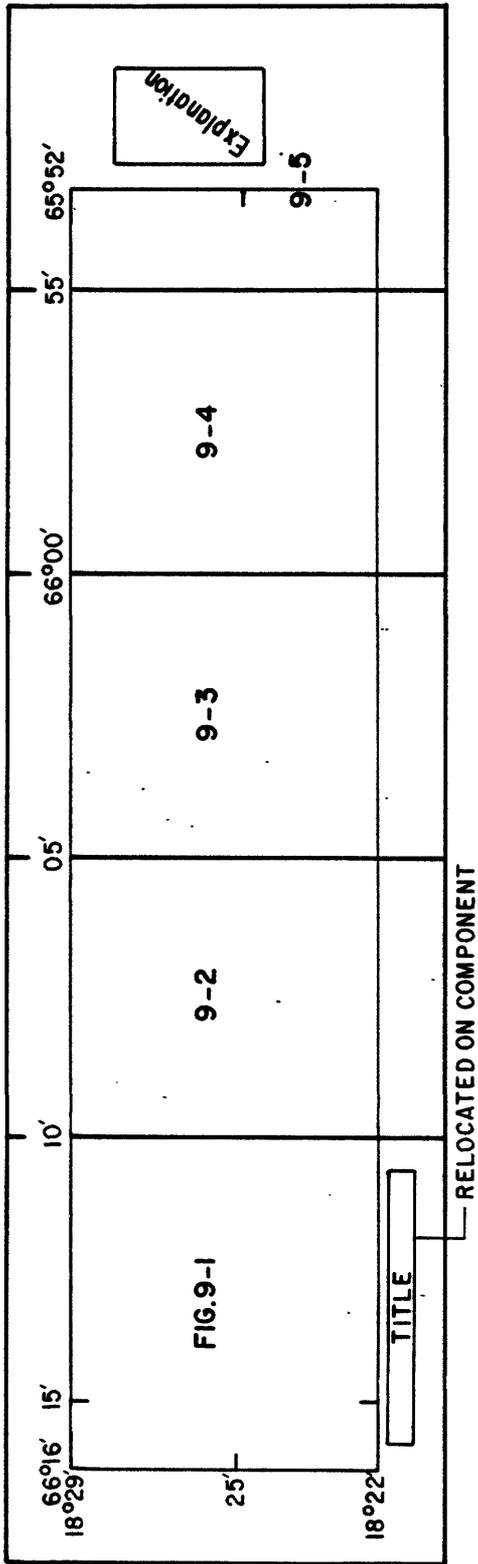
WATER-TABLE CONTOUR

Shows altitude of water in water-table aquifer. Contour interval, in feet (metres), is variable. Datum is mean sea level.

———15———

POTENTIOMETRIC CONTOUR

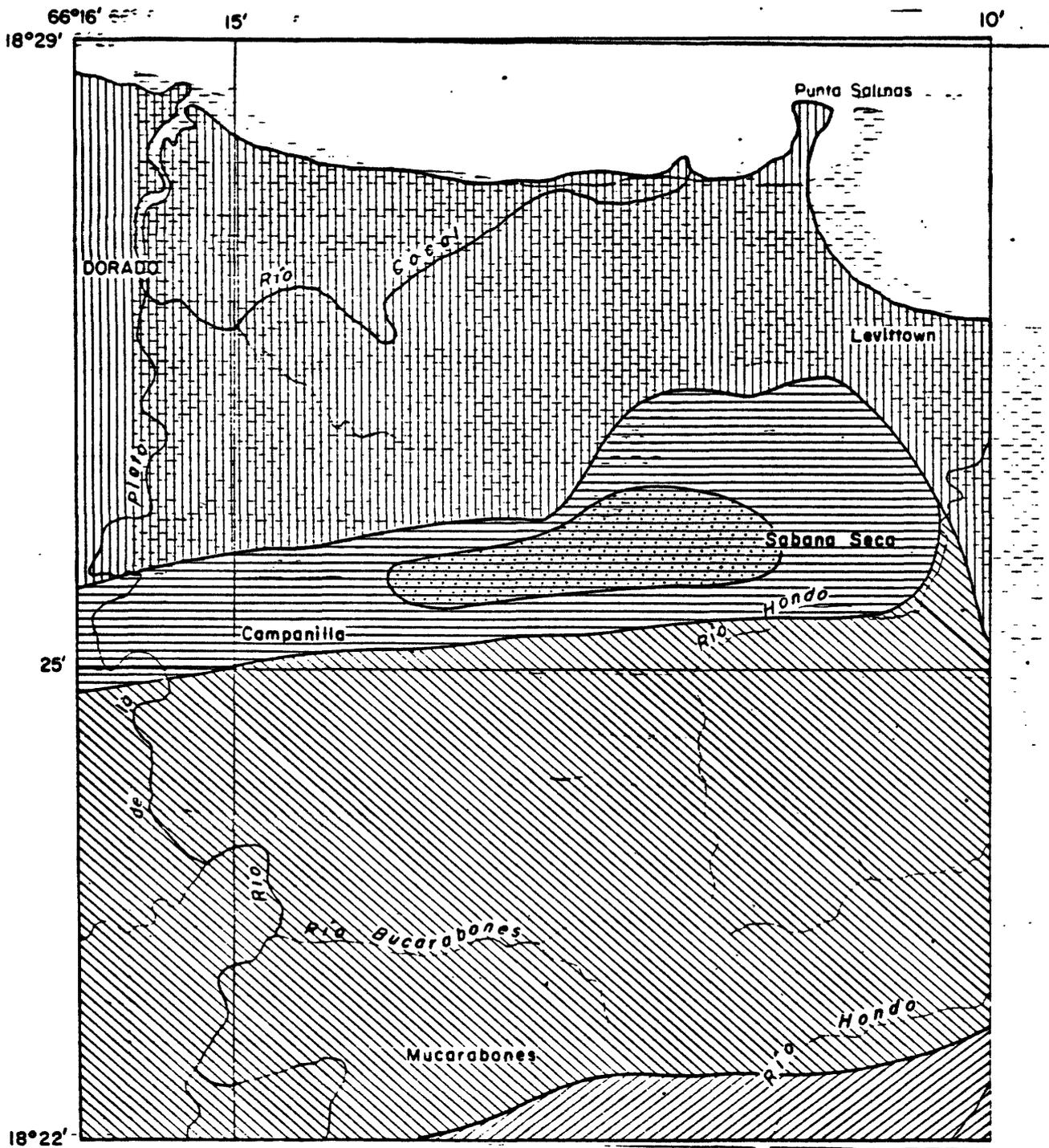
Shows altitude at which water level would have stood in tightly used wells in the artesian aquifer, (1971). Contour interval, in feet (metres), is variable. Datum is mean sea level.



(FIGURES 9 AND 13 COMPOSE THIS 18"x24" PLATE)

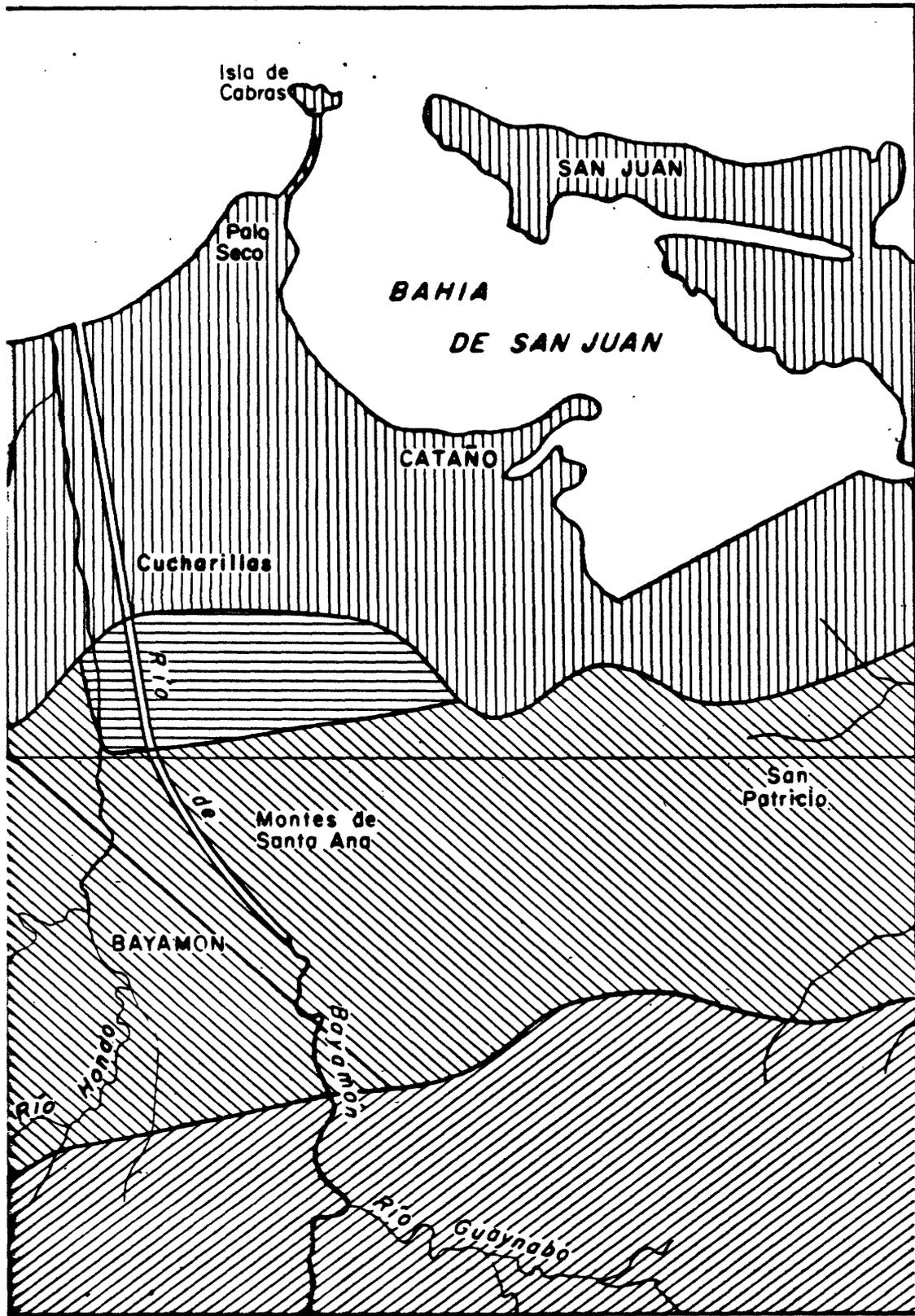
310

49



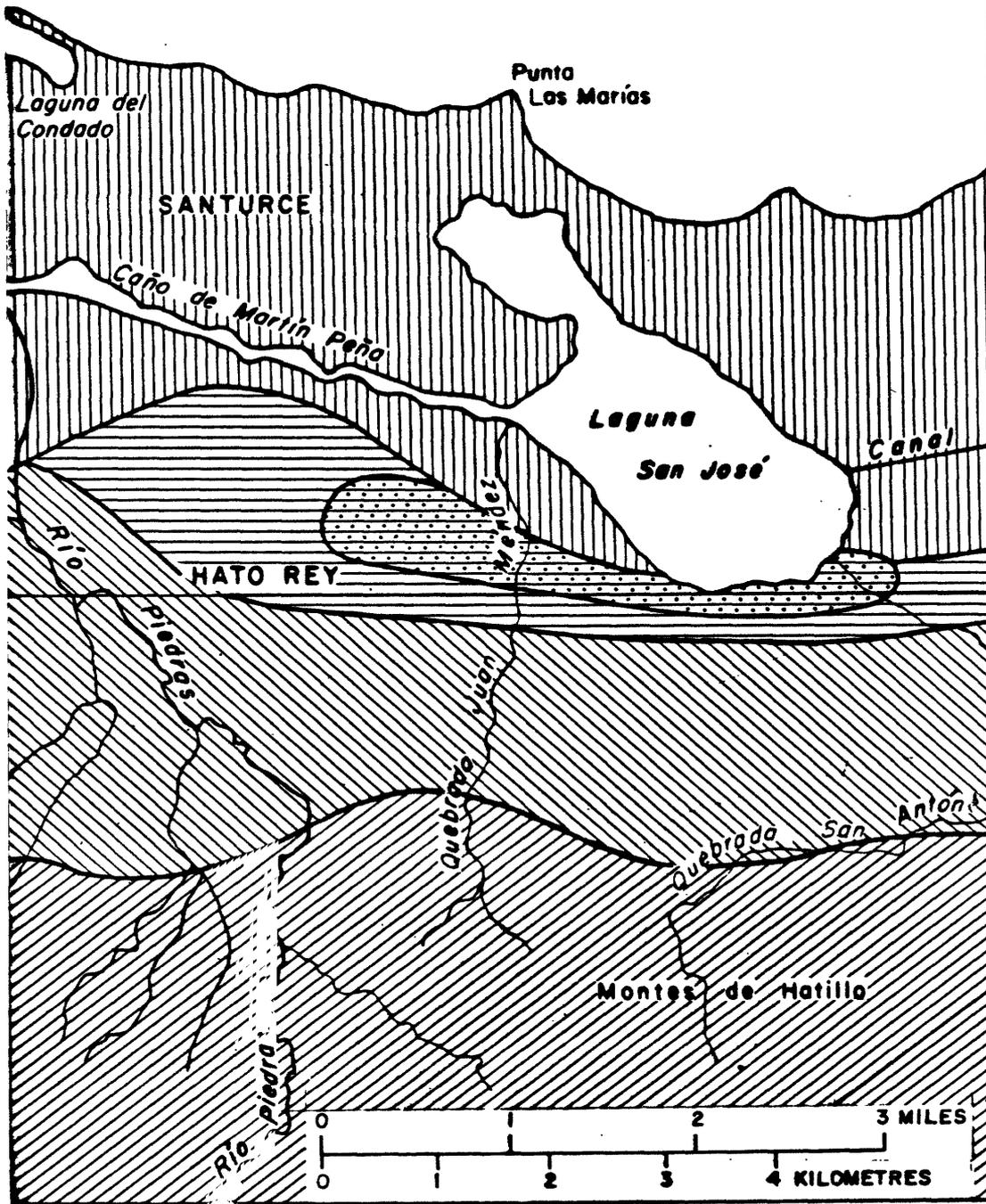
Base from U. S. Geological Survey map, 1:60,000, 1942

FIGURE 9 -- WATER-BEARING CHARACTERISTICS OF AQUIFERS IN THE SAN JUAN AREA. 9-1-80

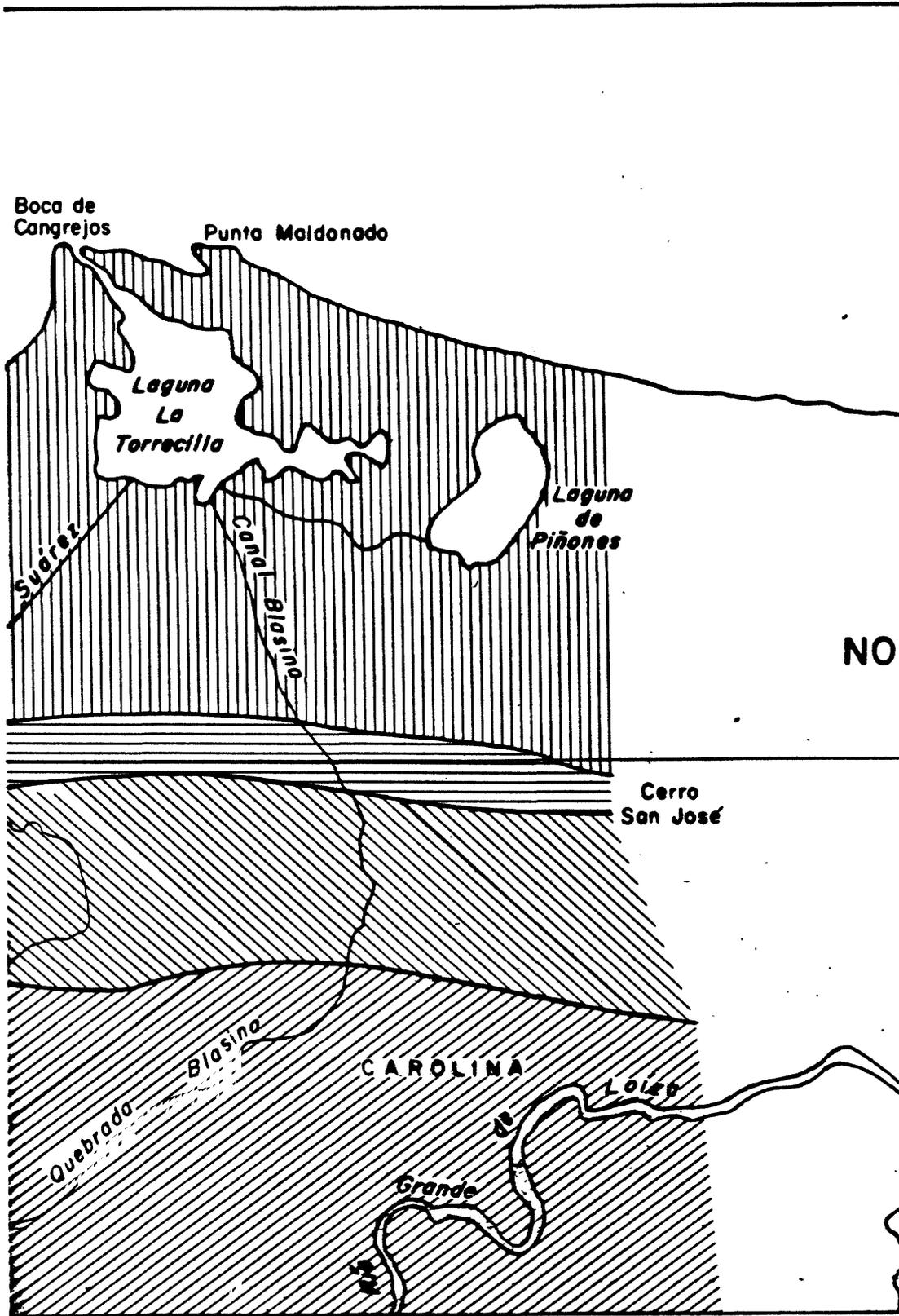


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82



NO

83

EXPLANATION



Low yields and salty water from surficial deposits.
 Large yields of salty water from underlying limestone.
 Possible moderate yields of freshwater from artesian sand aquifer below limestone.



Yields 30 to 2500 gal/min (2 to 160 l/s) freshwater from Aguada and Aymamon Limestones. Chance for salt-water intrusion lessens but yield declines to south. Average yield 515 gal/min (32 l/s). Specific capacity of wells 40 (gal/min)/ft [8.3 (l/s)/m] of drawdown.



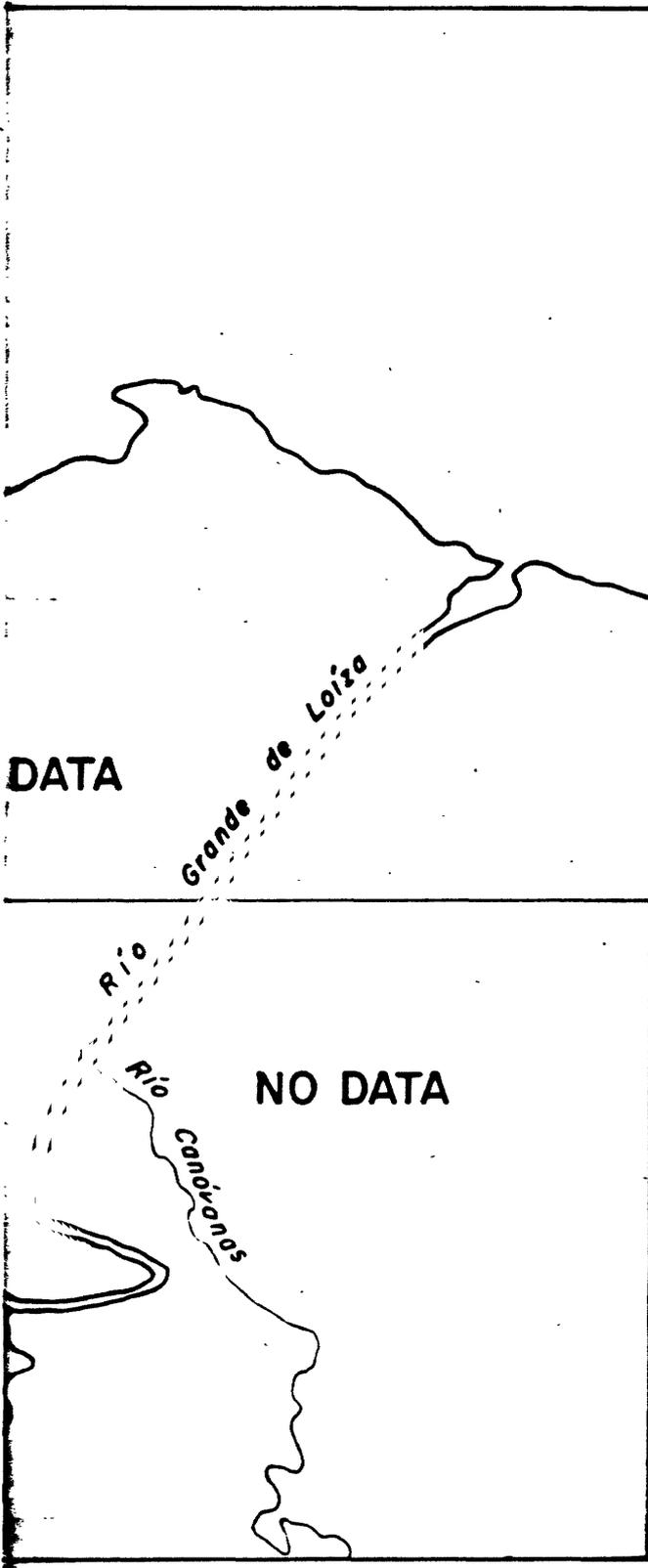
Yields 0 to 800 gal/min (0 to 50 l/s) of freshwater from Cibao and San Sebastian Formations. Average yield 120 gal/min (7.6 l/s) from Cibao and 244 gal/min (15 l/s) from San Sebastian. Specific capacity of wells 3.1 (gal/min)/ft [0.64 (l/s)/m] of drawdown for both formations.

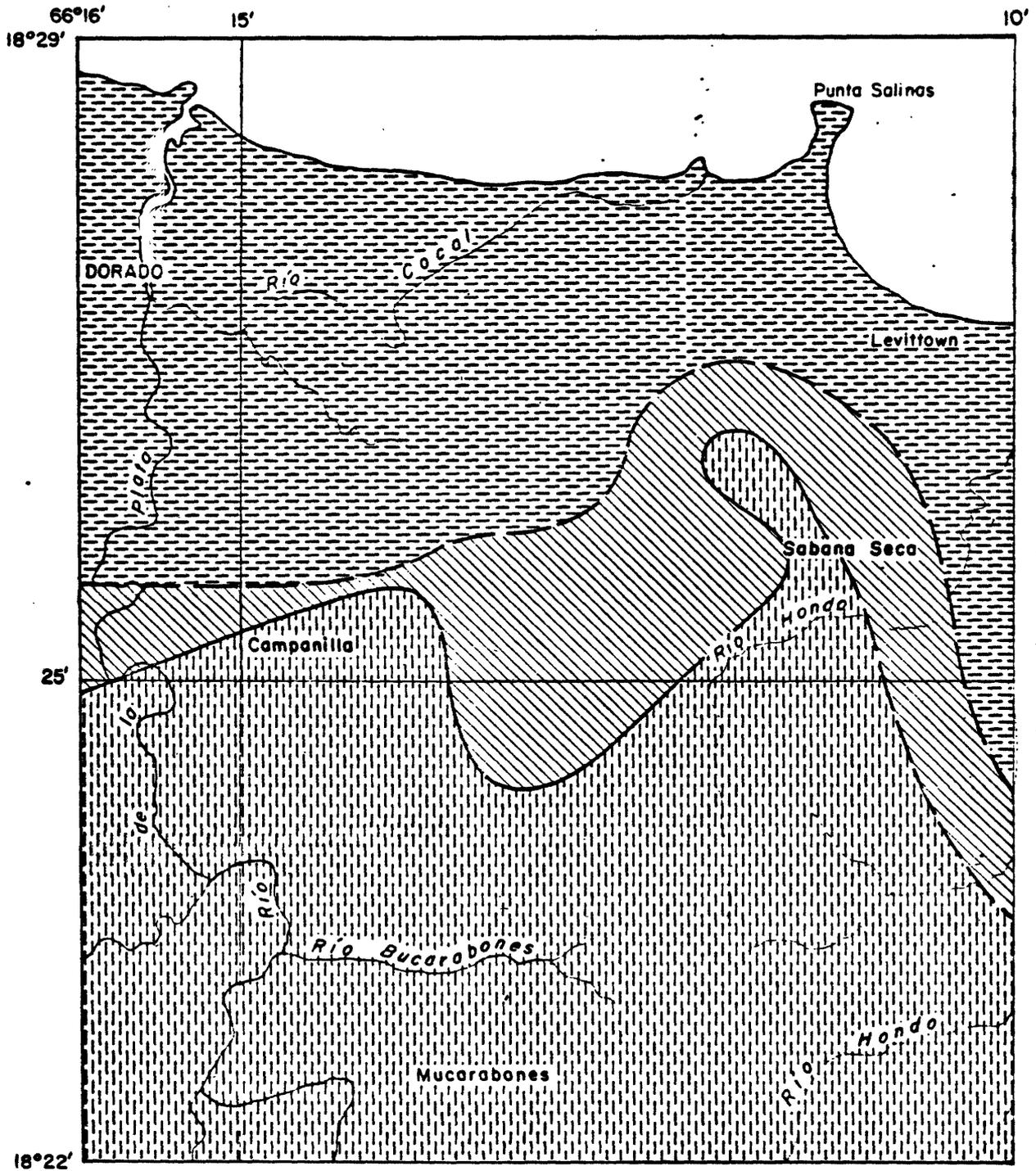


Generally low yields 0 to 300 gal/min (19 l/s). Average yield 50 gal/min (3 l/s) from weathered zone and fractures of volcanic rock.



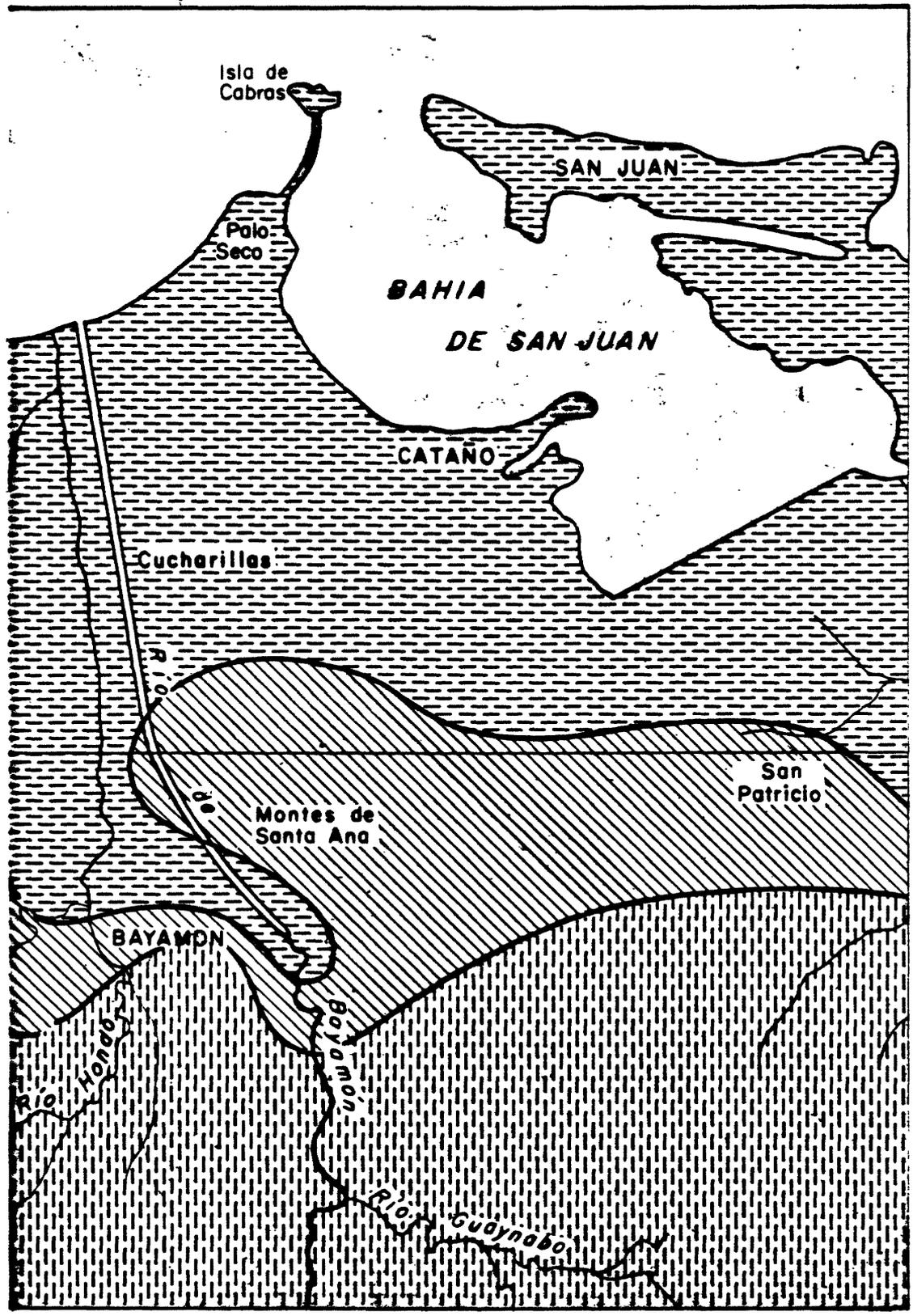
Possible areas for development of major supplies of ground water.



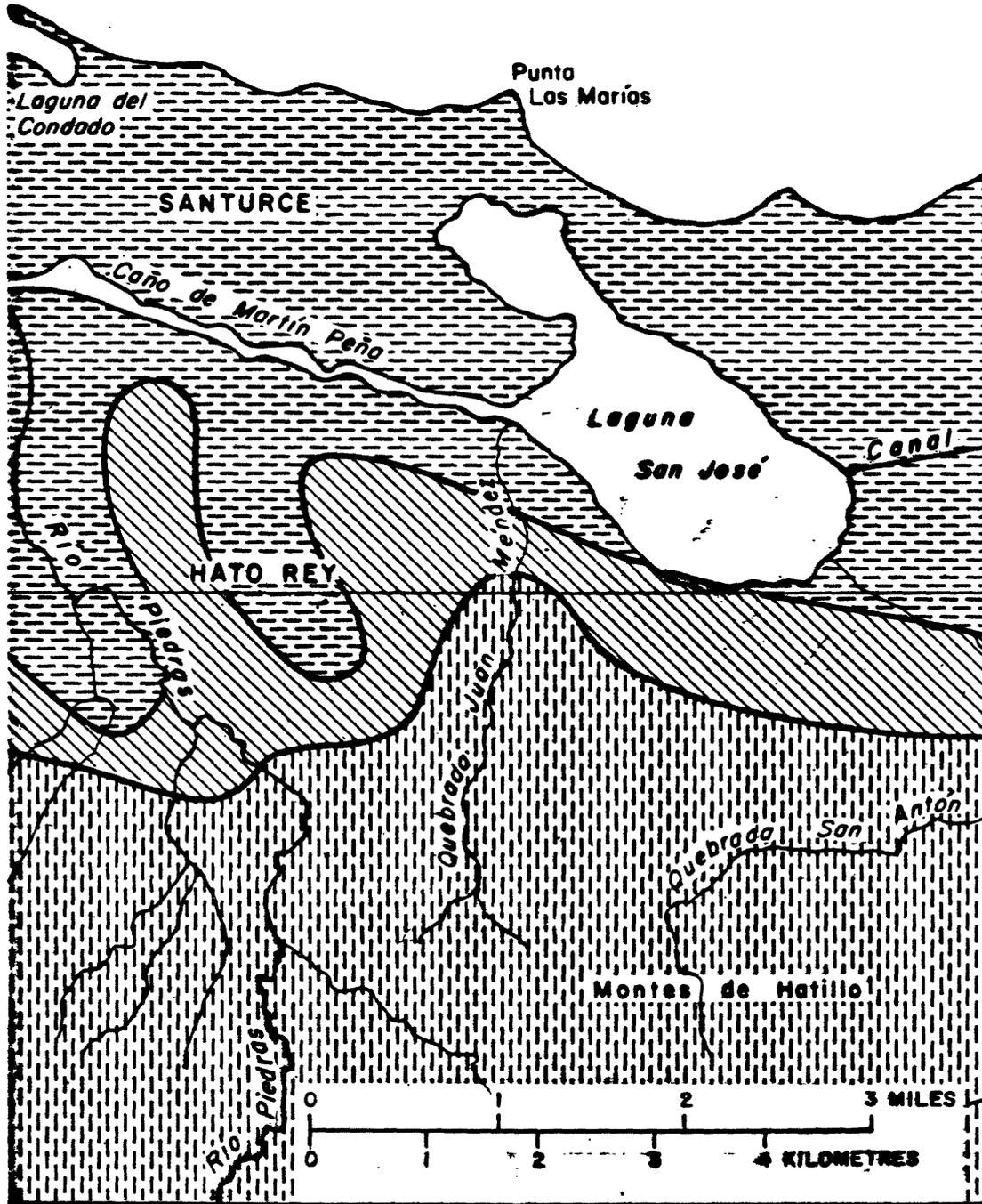


Base from U. S. Geological Survey map, 1:60,000, 1942

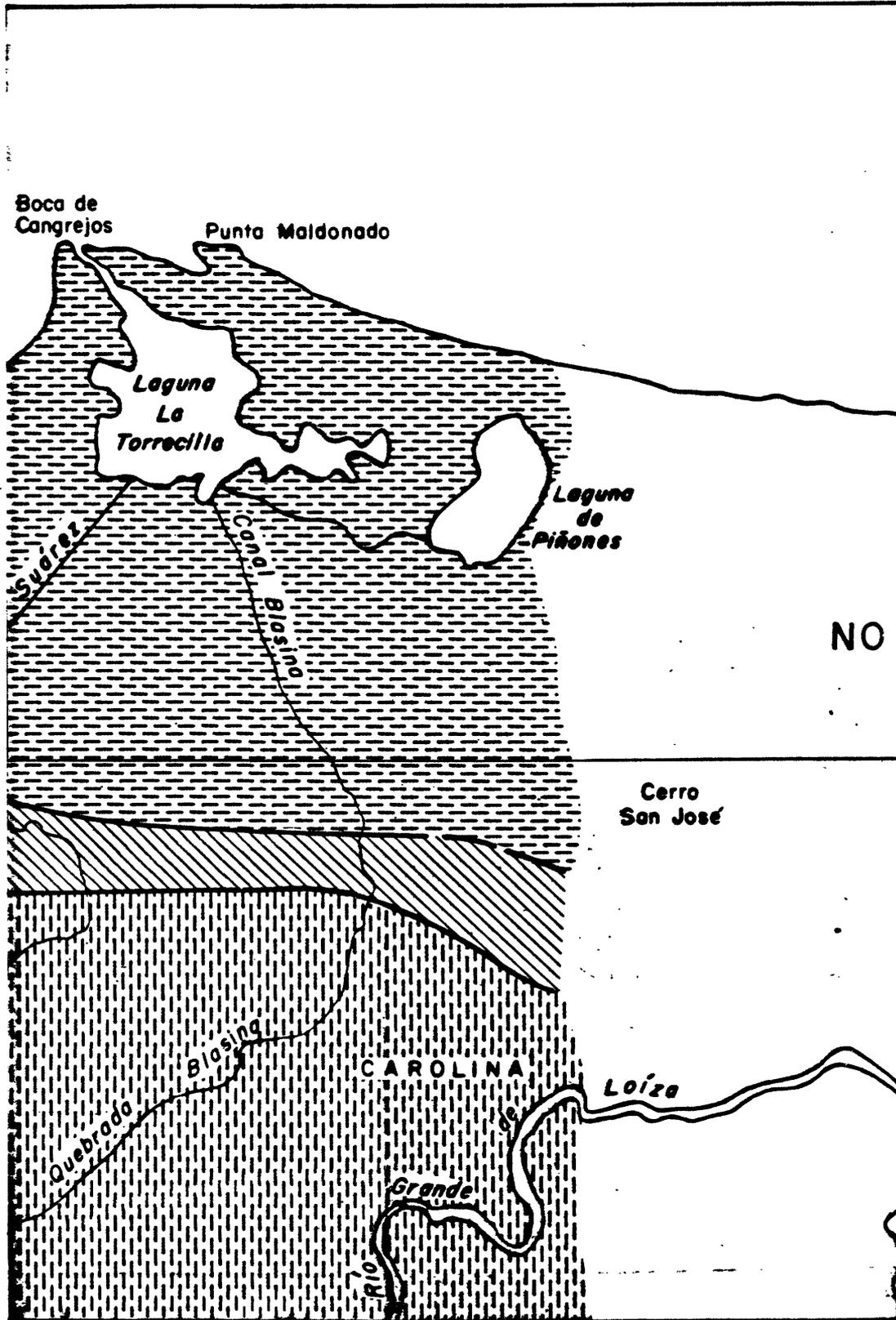
FIGURE 13 -- DISSOLVED-SOLIDS CONCENTRATION IN GROUND WATER, SAN JUAN AREA.



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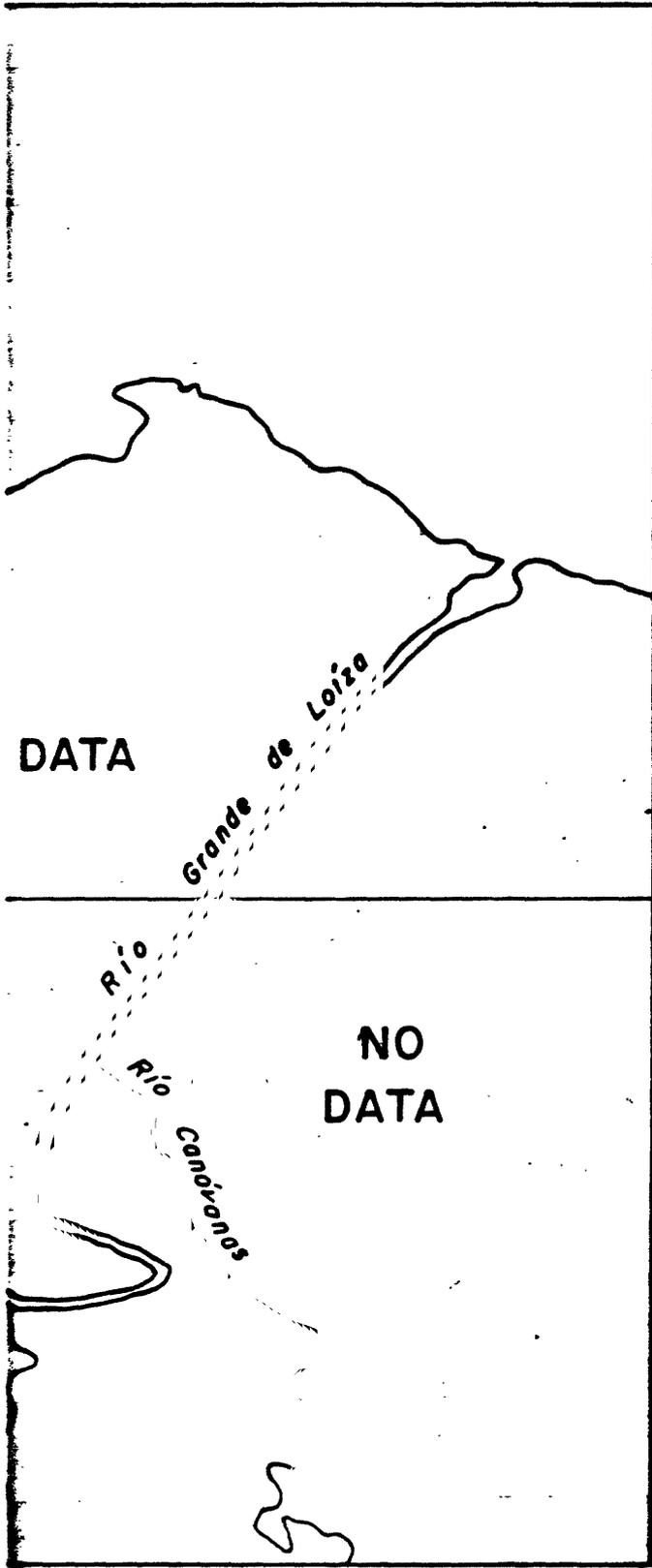


87



88

65°52'



EXPLANATION

Concentration of dissolved solids,
in milligrams per litre



Less than 300

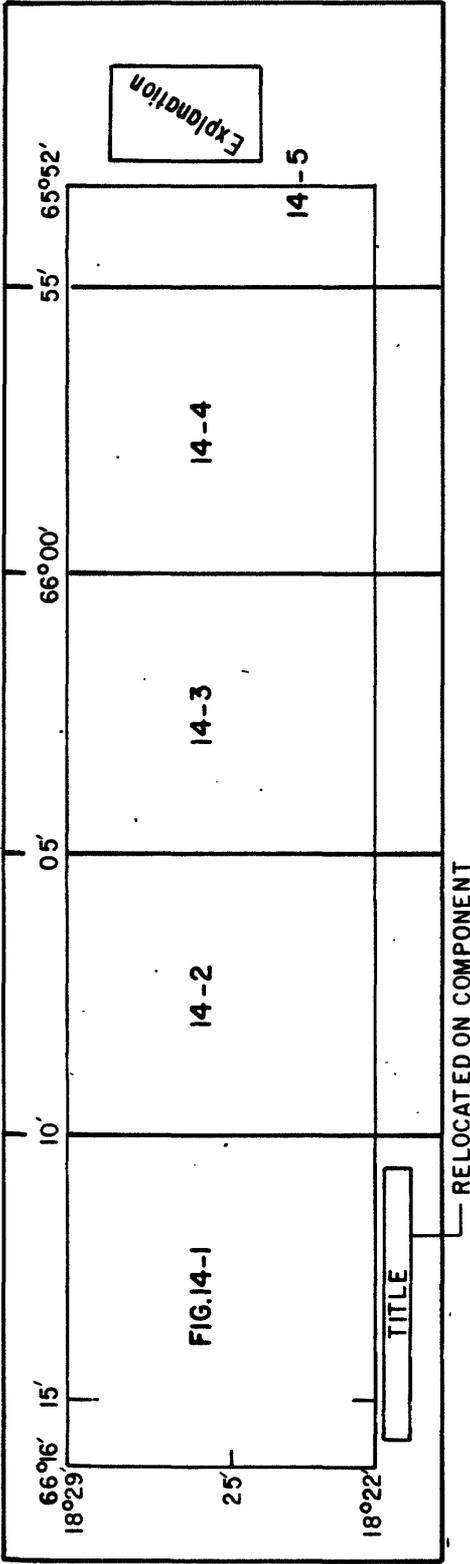


300 to 500

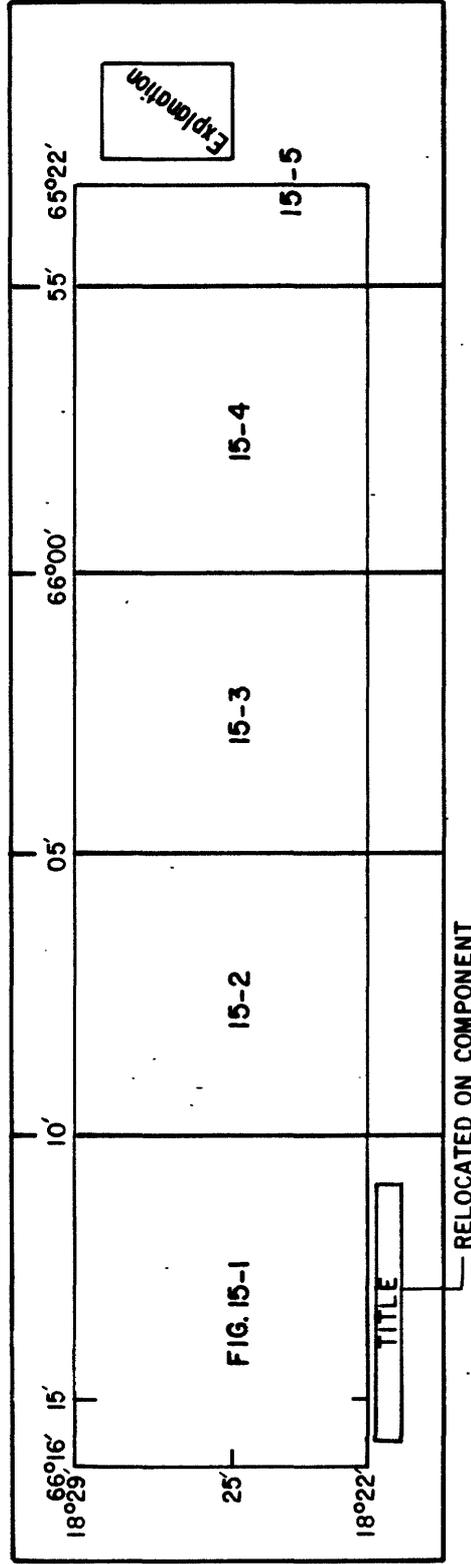


Greater than 500

89

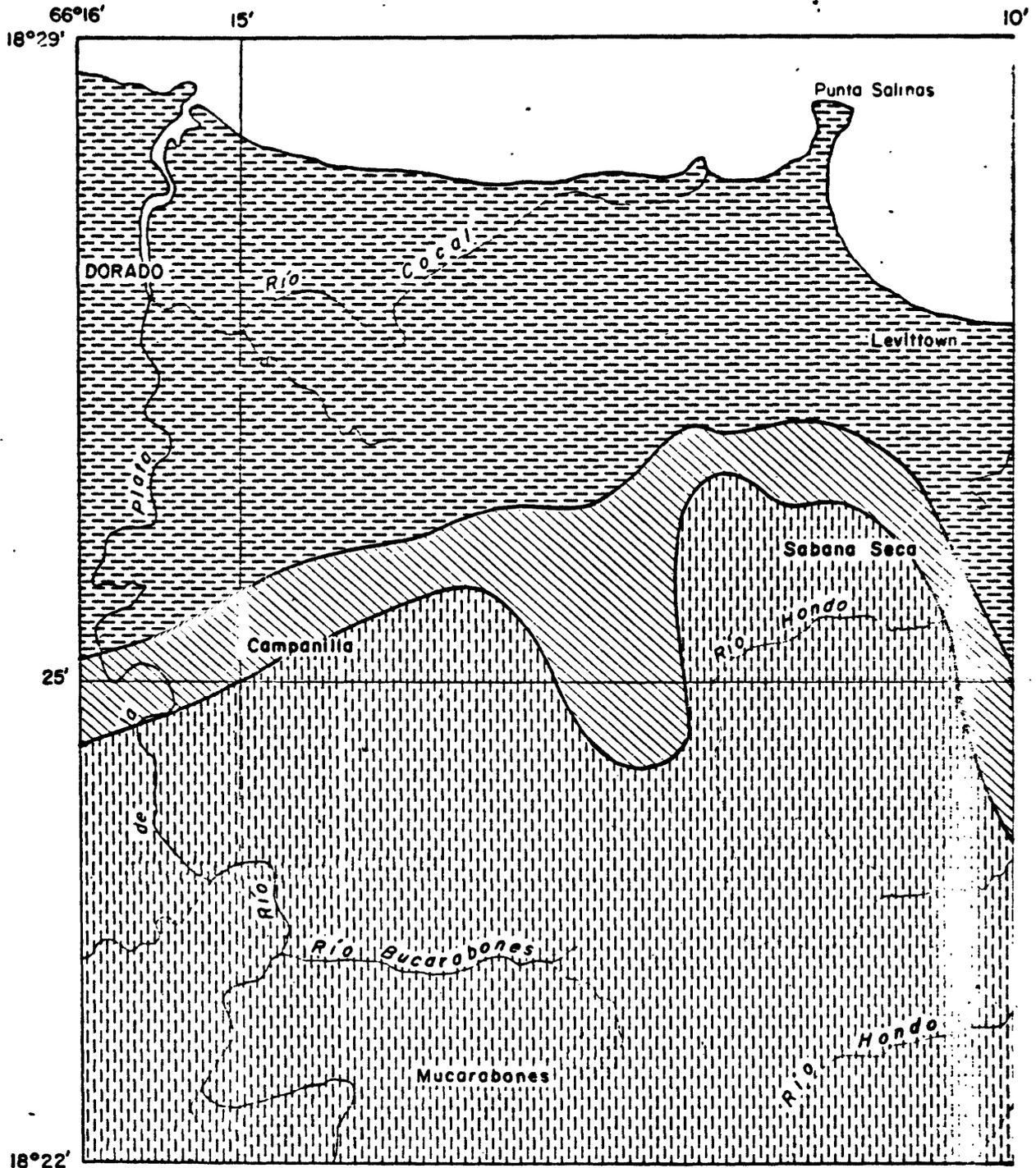


14 - 0
15 - 0



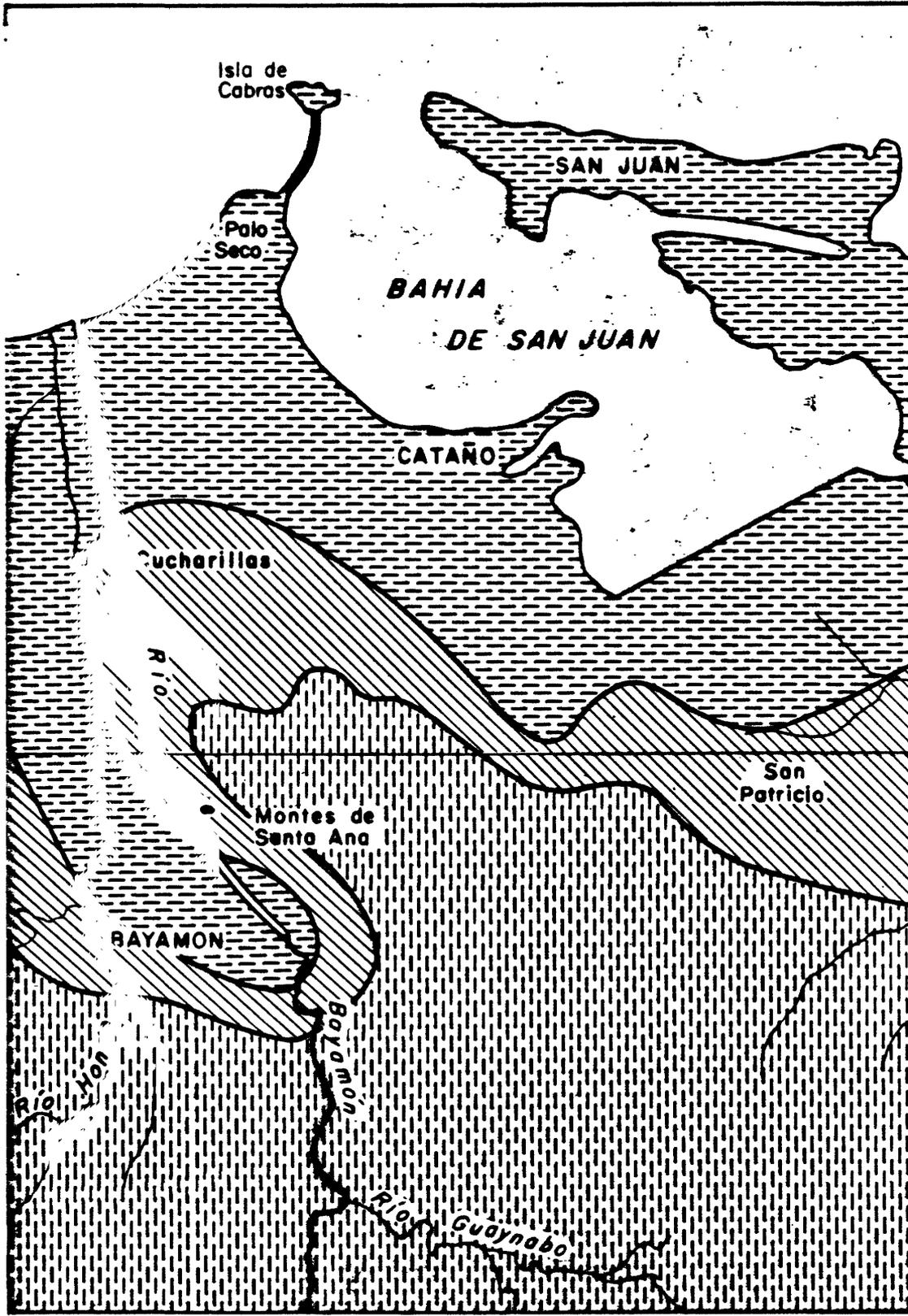
(FIGURES 14 AND 15 COMPOSE THIS 18" x 24" PLATE)

90

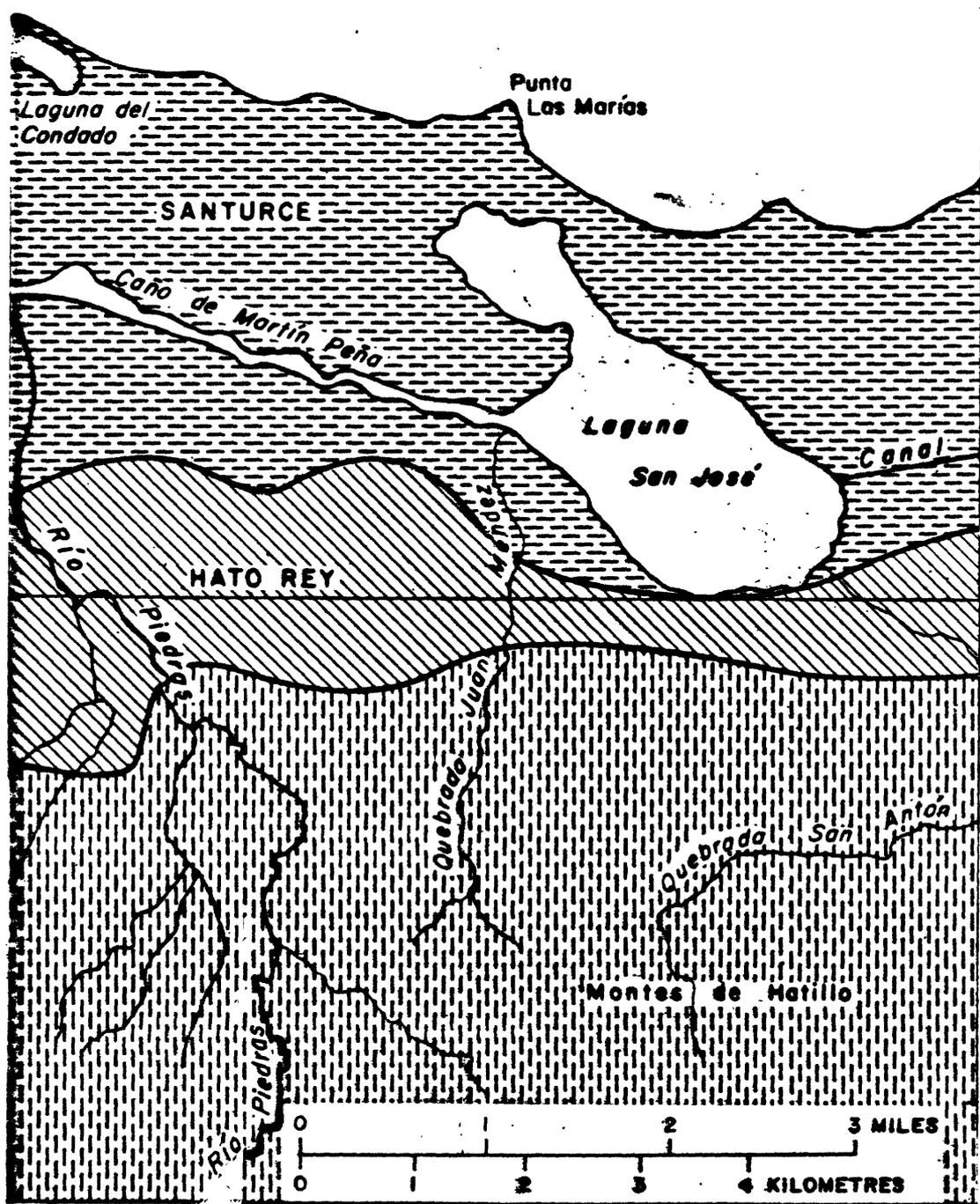


Base from U. S. Geological Survey map, 1:60,000, 1942

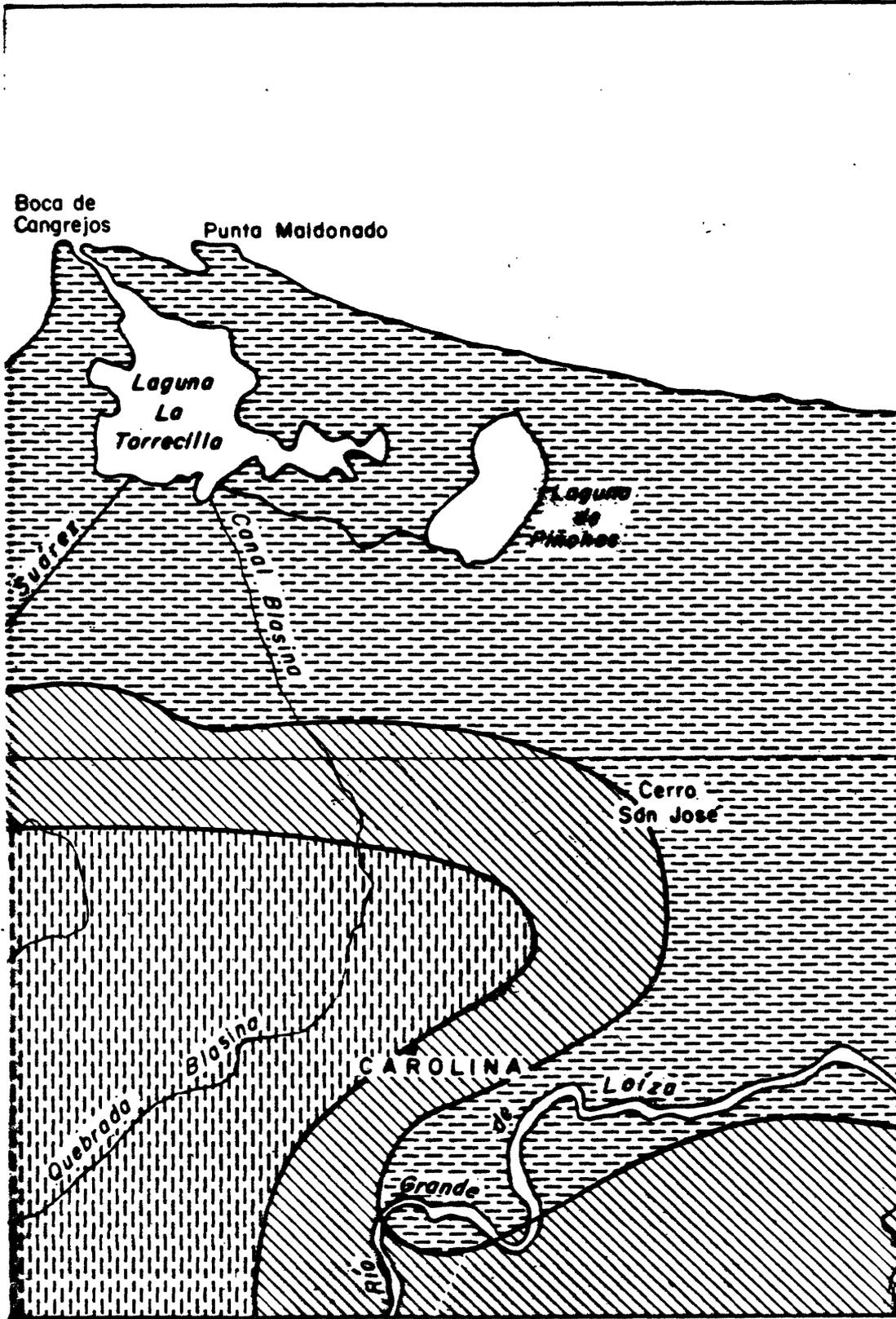
**FIGURE 14 -- CHLORIDE CONCENTRATION OF 91
GROUND WATER, UNCONFINED
14-1 AQUIFER, SAN JUAN AREA.**



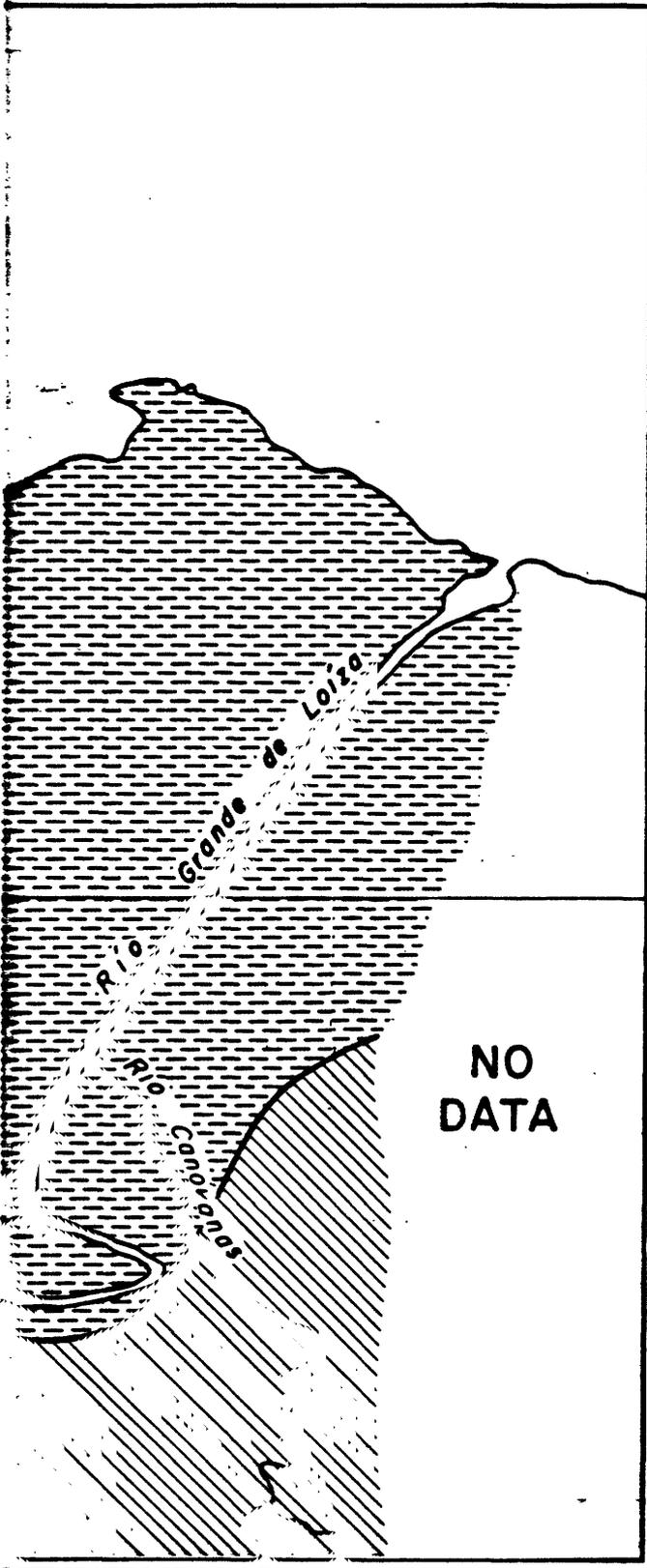
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EXPLANATION

Concentration of chloride,
in milligrams per litre,



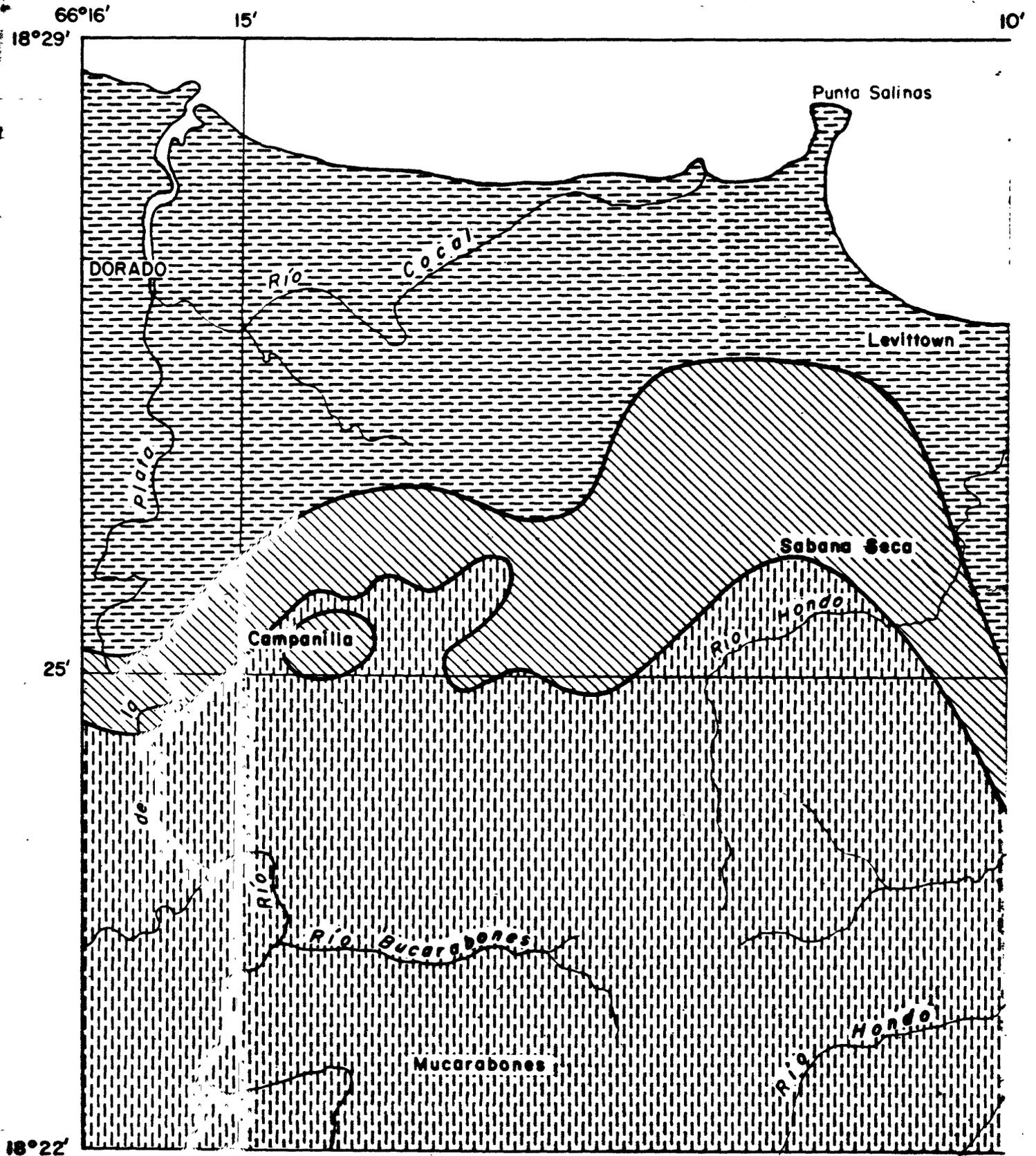
Less than 50



50 to 250

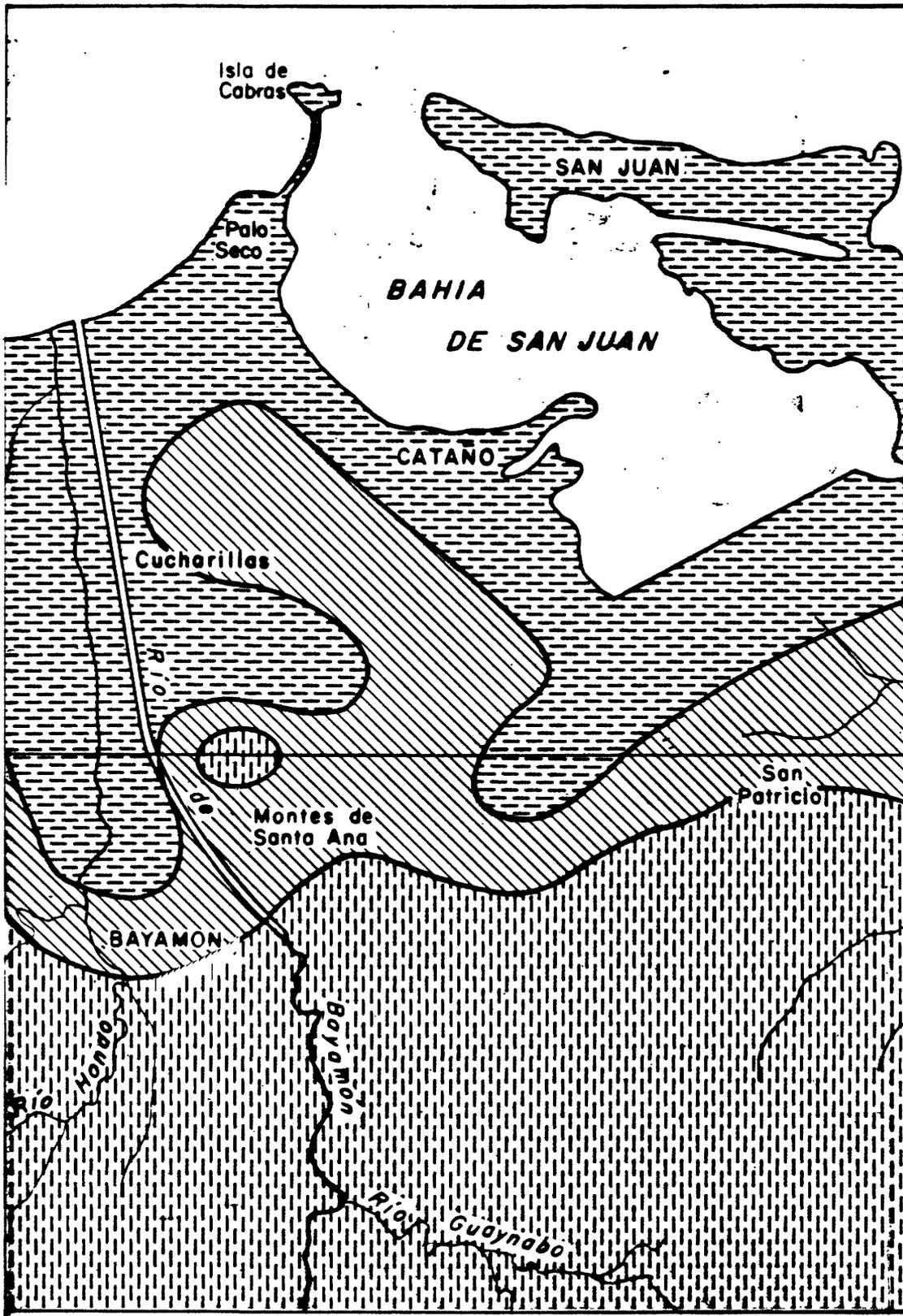


Greater than 250

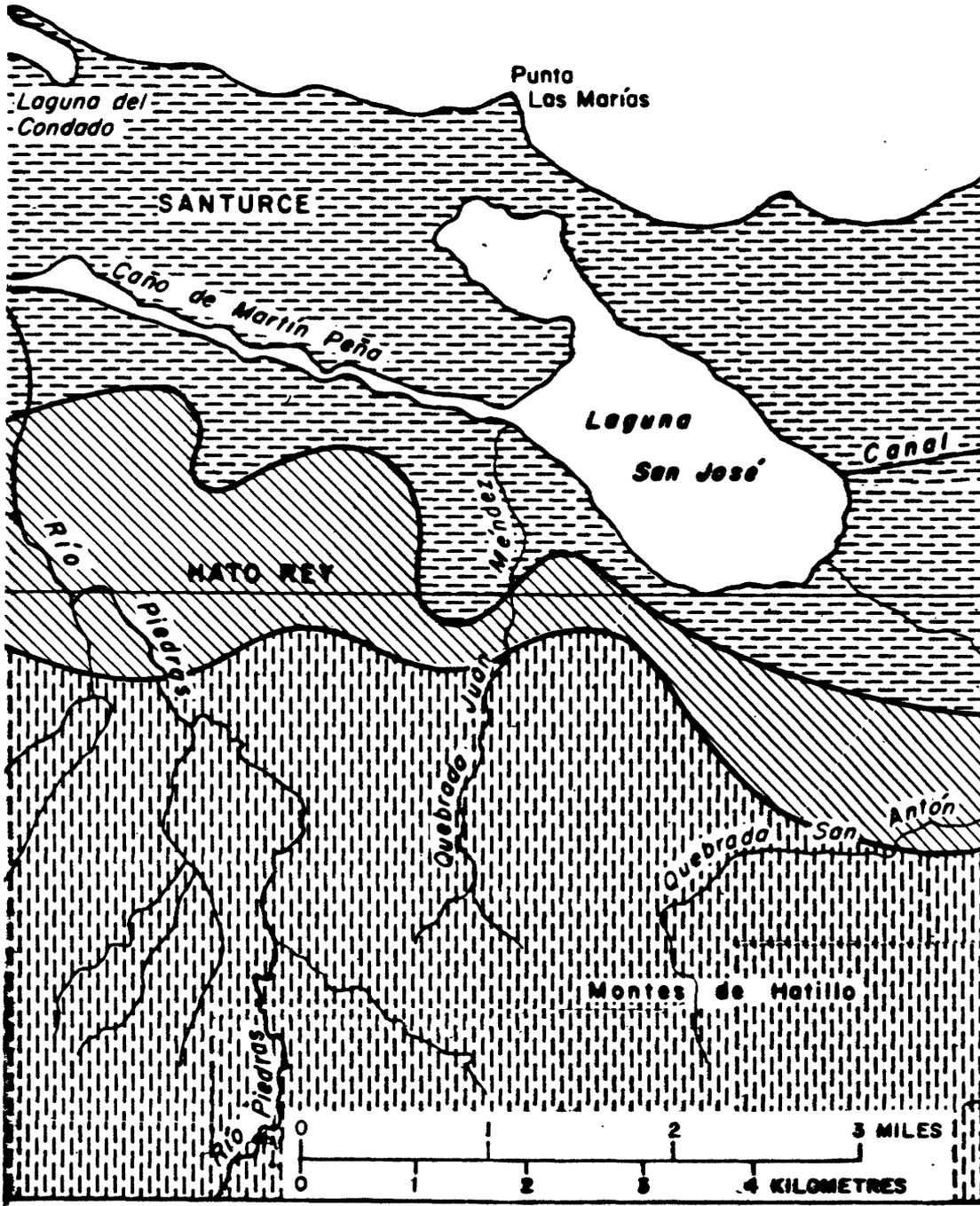


Base from U. S. Geological Survey map, 1:60,000, 1942

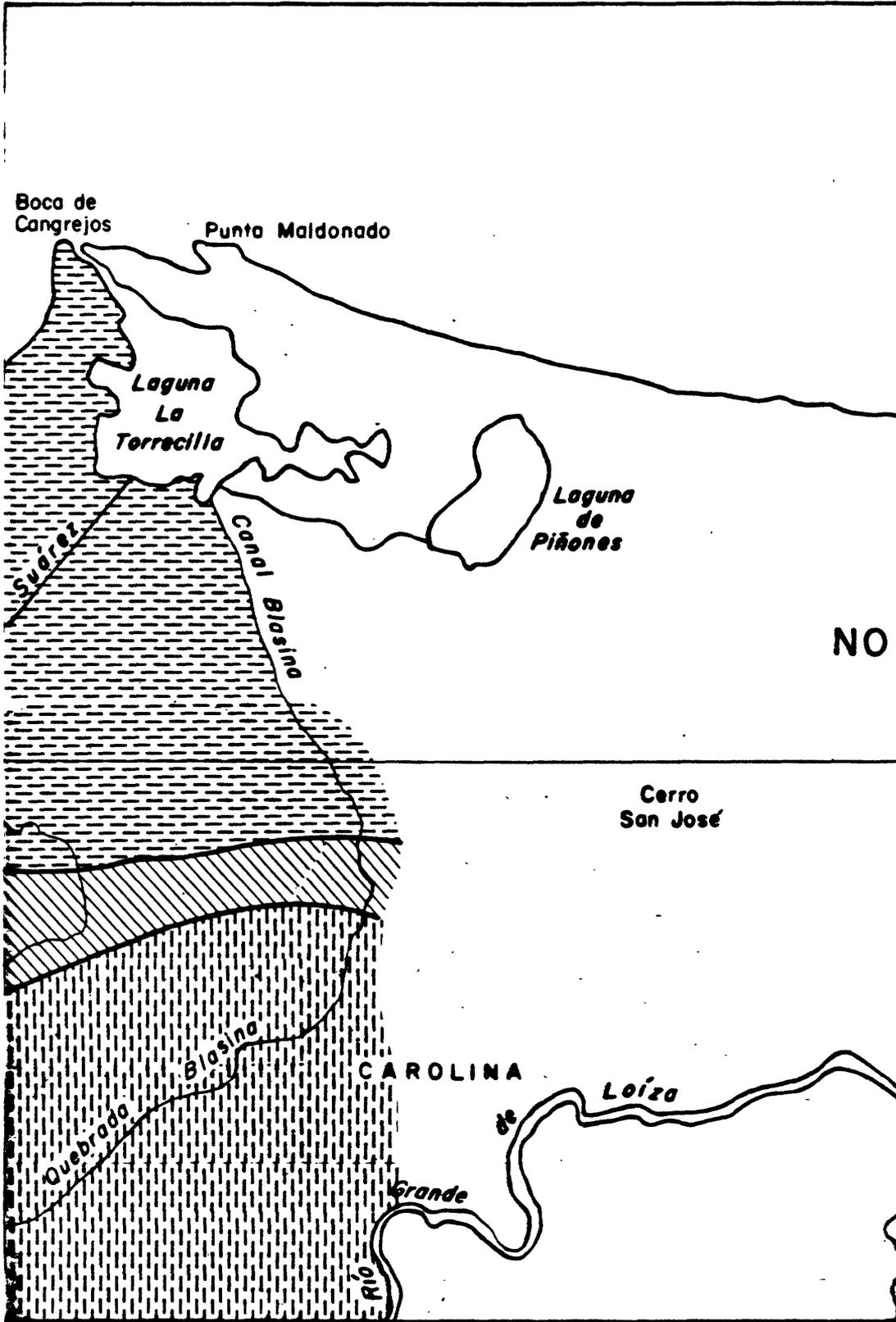
FIGURE 15 -- HARDNESS OF GROUND WATER, UNCONFINED AQUIFER, SAN JUAN AREA.



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NO

99